COMPUTER-AIDED PROCESS PLANNING AND FIXTURE DESIGN (CAPPFD)

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by

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To my wife, Prapai, and our children for
their support and encouragement

ABSTRACT

This thesis describes a computer program for process planning and fixture design. It utilizes the principles of workpiece control, in particular dimensional and geometric control, to sequence the machining operations and to design the 3-2-1 location systems.

The system developed uses the matrix spatial representation, a series of two-dimensional arrays, to describe the workpiece geometry. The system is capable of sequencing three types of machined features requiring milling operations: plane surfaces, slots, and steps. These features may be regarded as two-dimensional type: they can be completely specified dimensionally in two orthogonal projection views. Other data required by the system include the surfaces to be machined, cutting conditions, dimensions and tolerances of the stock and of the finished part. These data are either interactively input into the system or stored in a prepared data file for the system to read. The outputs include the process picture showing all locating surfaces in the 3-2-1 location system for each operation, and a set of three tolerance charts for analysing all dimensions of the machined part.

The results of this research indicate that the automatic machining sequence planning can be achieved through the implementation of the concept of workpiece control together with the practicality in machining a machined feature. The research also emphasises a significant role of the tolerance charts which have been used in manual process planning for a long time, but have not yet been exploited to its full advantage in computerised process planning. Regarding tolerance charts, the research has developed a new method for calculating tolerance stacks which can be used for computerized as well as manual charting.

The ideas presented in the report could be applied to the systems using a commercial solid modelling package.

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CONTENTS

1. INTRODUCTION

Process planning is the activity of planning the steps of manufacturing a product; the term is normally used in connection with metal machining. The task of process planning may include: selecting machine-tools and equipment to manufacture a product, planning the processing sequence, determining the methods for positioning and holding the workpiece during processing, specifying the appropriate cutting conditions, calculating the standard times, and producing the operation sheets for workshop use. Its scope may range from high level planning involving a number of machines or processes to low level planning confined to only one machine or process, in which the term is usually referred to as machining sequencing or operation planning.

Because the task covers a wide range of practical activities and know-how, process planning requires a highly skilled and experienced process engineer who has been on the job long enough to be well versed in the use of the machines, tools, and other auxiliary production equipment (such as jigs and fixtures). Unfortunately, the number of people available with these qualifications is diminishing, and it requires a long time to accumulate the knowledge and experience necessary to be a proficient process planner. As the batch manufacturing expands, the demand for process planners also expands. Hence a shortage of process planners is unavoidable; this problem has arisen in both the USA [1] and the UK [2]. In addition to the problem of numbers, manual process planning is subjective, inconsistent and time-consuming. Therefore attempts have been made to use computers to automate process planning. Towards the beginning of the 1980s, computerised process planning became a research subject in institutions all over the world. At present, Computer-Automated Process Planning, and Computer-Aided Process Planning (CAPP) are terms in common use in both manufacturing industry and academic engineering institutions.

Fixture design is another important pre-manufacturing activity which is concerned with designing devices to position and hold the workpiece while being machined, inspected, or assembled. In production machining, this area of design is usually the responsibility of the tool engineer or tool designer. The fundamental aims of using fixtures are to ensure the required degree of interchangeability of the parts and to increase the productivity. Formerly, this production device was known as a jig or a fixture: a jig was used in drilling operations and had a guide for the drill; a fixture was used on the machine where the device was moving or standing still while the processing operations were performed on the part, but there was no guide for tools or cutters. Nowadays, the terms are still commonly used on the shop-floor; however, in the literature, the term 'fixture' alone is often referred to both jig and fixture in the former context.

Like process planning, fixture design used to be regarded as an art; good tool designers had to strive for years, working in a workshop, to acquire the practical experience. Fortunately, the work on jig and fixture design has been well documented; useful guidelines for practical design are available in several books: in particular, those written by Town[3], Gates[4], Kempster[5], Cole[6], Wilson[7] and Donaldson et al[8]. Guidelines are also made available for an analytical approach to jig and fixture design, for example, the book written by Hendriksen[9]. These valuable guidelines have been adopted in industry and technical colleges for a long time. In the early 1980s, computers were introduced to aid fixture design; this opened up another branch of research: Automated Fixture Design (AFD).

Process planning and fixture design are so closely related that fixture design could be considered as a part of the whole process planning activity. This is because the design specifications for a fixture involve the machining sequence and the location systems for positioning the workpiece in the processing steps. These pieces of information are the results of process planning, and the tool designer can use them as a basis for designing or for selecting fixturing elements: locators, supports, and clamping mechanisms.

In the following section, the fundamental principles of process planning are briefly presented to describe the practical nature of this planning function, and its interconnection with fixture design.

1.1 Principles of process planning

Although process planning has existed since metal machining enterprises started to realise the importance of the planning activity to achieve the organization's goals, the publications that document the procedure for process planning are very few. Among them, the material contributed by Lander, L.C.[10] is of most value. This small book outlines the basic steps of process planning used in the General Motors Institute, more than 50 years ago; probably, there, the analytical approach of process planning was first started. The principles given in the book were later detailed by Dolye[11], and Eary and Johnson[12]. The discussion in this section is based heavily on these sources and the procedure recommended by the ASTME[13].

The general steps of process planning are as follows:

(1) Analyse the part drawings

In this first step, the part drawings from product engineering are carefully studied by the process planner with a view to facilitating and economizing the manufacture of the product. Any ambiguous dimensions, tolerances or specifications must be clarified by consulting with the product designer. The information concerning the conditions of raw materials is also of importance; particularly, if the materials are castings or forgings, irregular parting lines or flashes may cause locating problems. Changes in specifications of the design could be made with the consent of the product designer. Also at this step, some areas or surfaces on the workpiece which have a critical relationship with the other areas must be recognised; these critical areas may be the ones used as the baselines for dimensioning, the areas which need a very close tolerance control, or the areas that have an effect on the functions of the product: for example, a surface which requires a very high surface finish but is not used as a baseline for dimensioning. These critical areas directly affect the sequence of operations required to transform a raw material to a finished product.

(2) **Determine the manufacturing methods**

After studying part drawings, the process planner has to choose the appropriate methods for manufacturing the product; that is to say, to determine the types, sizes, and capacities of the machines to be used in processing the workpiece. In metal cutting, the conventional machines are lathes, shapers, drilling machines, grinding machines and milling machines; these machines may be manually operated, semi-automatic or automatic. There are also special type machines which are designed and build for special machining operations; this type of machine has a higher rate of production than the general purpose machines: its cost is also higher. The process planner with a thorough understanding of machining processes should select the machine for a particular operation not only on the grounds of process capability, but also those of production economy.

(3) Plan the sequence of operations

Having made the decision on the processes to be used, the process planner then plans the sequence of operations. In this phase of analysis, there are normally more than one solution applicable to a single problem. Nevertheless, some of the solutions are better than the others; therefore, the task of the process engineer is to ensure that a better solution has more chance of being found. To this end, the following concepts and principles should be adopted:

(a) Concept of critical areas:

As mentioned in the first step, a critical area is the one which is more important than the others on the workpiece; it also requires special precautions during processing. Critical areas can be classified into two categories: process critical areas and product critical areas.

Process critical areas are those areas that have a critical relationship with the other areas of the workpiece. In the drawing these areas are identified by baseline dimensioning. Because these areas affect the control of other dimensions directly, they are used as the registering or locating surfaces for positioning the workpiece.

Product critical areas are the areas on the workpiece which govern the functional performance of the product. These areas may or may not have a direct influence on the dimensional control of the part. They are often indicated by drawing specifications such as close tolerances, roundness, concentricity, flatness, squareness, and surface finish.

As an example, in Fig.1.1, if the holes are dimensioned with close limits from two edges, the surfaces at the two edges are the process critical areas; but, if the two hole diameters and the distance between them are to be held with a close tolerance -- because the holes have to be fit properly with other parts and the centre distance is critical for functional reasons of the assembly, then the two holes are both product and process critical areas. These critical areas have an important bearing on the sequence of operations; therefore, it is essential that all surfaces of the workpiece be classified, for effective planning of the process.

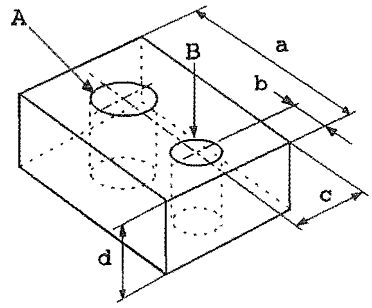


Fig.1.1: A plate with two holes.

(b) Operation classification:

All the operations should be classified into the following types: critical operations, secondary operations, qualifying operations, requalifying operations, auxiliary operations, and supporting operations.

Critical operations are those used for processing the critical areas, areas that required a close control on certain characteristics as described above.

Secondary operations are the operations performed on the areas which are less critical and generally require normal standard tolerances on dimensions, no special efforts being needed to accomplish them.

Qualifying operations are those operations used for getting the workpiece out of a rough condition. These are the first operations to establish a newly machined surface for locating a workpiece.

Requalifying operations are the operations that are required to re-establish a locating surface; this usually occurs when the part has experienced any physical change during the machining processes or heat-treatment: such as, distortion from stress relief, or surface damage due to clamping.

Auxiliary operations are those operations which change the physical characteristics or appearance of the workpiece. Examples of operations in this category include welding, heat treatment, finishing, and cleaning.

Supporting operations are the operations required to complete the product successfully. These operations can not exist by themselves. Operations such as shipping, receiving, inspection and quality control, handling, and packaging fall into this category.

The general rules regarding the sequence of critical and secondary operations are:

- In order to reduce the tolerance stacks, the critical operations that establish the baseline dimensioning should be performed as early as possible in the sequence.
- The critical operations, on the areas which require close tolerance control, should be accomplished as early as possible in the sequence. This is because the surfaces may be used as the locating surfaces for other machining or gauging operations, Another reason is to save the operation costs: if the part is likely to be scrapped, it should be allowed to happen as early as possible.
- The critical operations that relate to the product critical areas should be carried out as late as possible in the processing sequence. The

reason for this is to avoid any surface damage that may occur in the later steps of manufacture.

For other classes of operations, their order of placement in the sequence are largely governed by the critical operations.

(c) Principles of workpiece control:

From the above discussion, the process critical areas are to be machined before other less important areas in the processing sequence. However, on a workpiece there are usually several such areas; thus, a procedure is required to determine the priority to be assigned to each area to be machined. The priority assigned depends upon the amount of workpiece control that each area can offer. Three types of workpiece control must be considered are:

- **Geometric control:** Geometric control relates to the stability of the workpiece due to the geometric disposition of locators; for example, the surface on which the locators can be placed wider apart gives a better geometric control.
- **Mechanical control:** Mechanical control relates to the resistance to movement of the workpiece under the cutting forces. The degree of this control is reflected by the amount of workpiece deflection under the cutting and holding forces.
- **Dimensional control:** Dimensional control relates a direct effect on the dimensional tolerances achievable on the machined part, which, eventually, are the quality characteristics of the product. Therefore, it is the most important control of all the three. Good dimensional

control is characterized by no tolerance stacks, and is achieved by placing the locators on appropriate surfaces.

(d) Concept of workpiece locating:

A dimensions of a machined part is, in fact, the distance between the surface of a locator and the cutting edge of a tool. So, to ensure the uniformity in dimensions, every workpiece must be placed, as far as possible, in the same position while being machined.

The concept of workpiece locating here is concerned only with the use of locators to constrain the workpiece in a required position; it has nothing to do with the holding forces. The general concept of locating can be stated as: to locate an object in any position is to deprive the object of its six degrees of freedom -- three translations and three rotations (Fig.1.2).

When the workpiece is constrained by locators, like the ones in Fig. 1.3, all the degrees of freedom are stopped by the six locators. This arrangement of locators is known as the 3-2-1 location system, in which three locating surfaces on the workpiece must be mutually nonparallel, (preferably) perpendicular planes. On some workpieces, these locating surfaces must be established if they do not exist. This may be achieved by incorporated them in the design of the part, and they may be machined out in a later step of machining, or they may be left on the finished part.

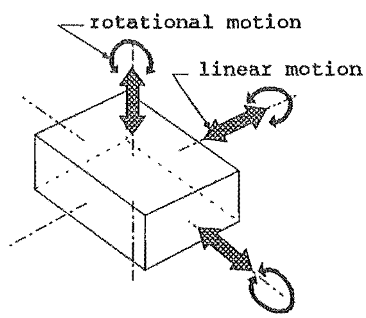


Fig.1.2: Six-degree of freedom.

The positions of the locators on each surface depend on several factors; the more important ones are the surface conditions, size and type of the surface, type and size of locators, and the degree of workpiece control.

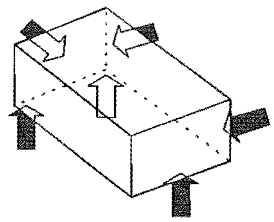


Fig.1.3: 3-2-1 location system.

From the concepts and principles discussed above, the sequence of the processing operations is dictated mainly by the control of workpiece dimensions, which is influenced directly by the positions of the locators. Therefore, the location system for the workpiece in each machining operation is of vital importance in process planning.

(4) Construct the tolerance chart

Tolerance charts are a graphical means of representing the changes of dimensions and tolerances of the workpiece at each machining step of manufacture. They are a powerful tool used to check for any tolerance problems in the machining process prior to the actual manufacture.

During the final step of process planning, a tolerance chart is usually constructed to check if the sequence and tooling have been properly planned. If the design specifications can not be achieved as verified by the tolerance chart, the sequence, tooling or specifications must be changed.

(5) Fixture design

The role of fixture design starts when the operations sequence has been completed [9]. Traditionally, the task of tool designer includes: studying the drawings of the part and the stock material; defining the positions for locating, supporting and clamping the workpiece; and designing the fixturing elements. However, if the fixture design is viewed as an integral part of process planning, these pieces of information have already been established when the operation sequence was planned. The tool designer can obtain this information from the process engineer and use it directly in the designing of the fixture. There is no need to replicate the task at the level of tool designer. The main concern of the tool designer is to design the fixturing elements, or choose them from available standard elements, and to make sure that all the requirements entailing the workpiece and cutting tool are functionally and economically achievable.

1.2 Literature review

It has been generally accepted for some time that process planning is an important link to bridge the gap between design and production. In the present advanced environments of Computer Aided Design (CAD) and Computer Aided Manufacturing (CAM), Computer Aided Process Planning (CAPP) is an important key to the success of fully computerised manufacturing, which is often referred to as CIM (Computer Integrated Manufacturing).

There are two basic approaches to computerised process planning: the variant approach and the generative approach. Variant process planning is based on a predefined processing sequences for families of parts, these being stored in a suitable form of database in the computer. This type of process planning system usually requires a coding system for identifying the part family, and therefore it is closely associated with the use of Group

Technology techniques [14]. To plan the processing sequence for a new part, the characteristics of the part are coded; the code is then used to retrieve the processing sequence from the database. The advantage of these variant systems is that they are easy to develop and implement, and suitable for a large number of different parts that can be grouped into a small number of families. The main weak points of the systems are that they still require human intervention during the planning stage; this may be necessary even if there is only a slight difference in the design of the part being planned from those whose sequences are already stored in the database. Typical variant process planning systems are MIPLAN [15], CAPP-CAM-I [16], GENPLAN [17], and Micro-CAPP [18].

The generative process planning system embodies the manufacturing logic and uses it to generate the processing sequence for a part. The limitation of the system depends only on the logic stored. Because this manufacturing logic is compiled from experiences (know-how of the process planners) and from other relevant scientific knowledge, this type of process planning system is more difficult to develop than the previous one. Nevertheless, the system can offer fully automatic planning without human intervention. This makes the development of the system more challenging. Since Wysk proposed the idea of automatic generative process planning in 1977, the approach has become widely researched in both industry and universities. Examples of this type of process planning system include TIPPS [19], CMPP [20], and AUTOPLAN [21].

There are also the systems that make use of both approaches. In these systems, both variant and generative properties are built into a single system. For example, ICAPP, which developed by Eskicioglu and Davies [22], is capable of selecting the machining sequence for a part from each of a number of families of parts stored in the system; and, to some extent, it can also generate the plan according to the logic defined by the system.

Up to about the beginning of the 1980s, many research groups realised the difficulties in encapsulating manufacturing logic using the conventional programming methods. During the same period of time, Artificial Intelligence (AI) research has produced some successful results in areas such as medicine, chemistry, oil-field exploration, and computer configurations. These and many other successful systems based on AI techniques have inspired manufacturing researchers to launch the research using AI techniques. By the middle of the 1980s, several AI based systems for process planning had been developed. The systems incorporating AI techniques are known as rule-based, or expert process planning systems. The attractive characteristic of the expert system is that the manufacturing logic of the expert is stored in the form of rules and these rules can be interpreted and used to infer appropriate decisions. Examples of AI based CAPP systems include GARI [23] and EXCAP [24] for machining rotational parts, and the system developed by Iwata and his research group in Japan [24], EXPLANE [25], and HutCAPP reported by Mantyla [27] in Sweden for prismatic parts. Although AI seems to be a promising technique for process planning (in which its application is growing rapidly) there are some basic problems in developing an expert system: firstly, there must exist an expert in the problem domain of interest; secondly, the appropriate means must be available for knowledge acquisition; and thirdly, it requires time. These problems make the real practical expert system difficult to develop [28].

In developing a CAPP system, the method for representing the part in the computer is also of vital importance. The requirement is that the method used should be able to provide both the geometric and the manufacturing information of the part. This has drawn other areas of research: such as, solid modelling, feature recognition, and design by features, into the province of CAPP research. The systems that reflect this multi-disciplinary knowledge are, for examples, the expert system developed by Willis et al [29], EXPLANE [26], STOPP [30], and FORM (Feature Oriented Modelling) [32].

Alting and Zhang[32] have made a comprehensive literature survey of the state-of-the-art of CAPP systems, which has covered more than 200 published papers from all over the world, and more than 150 CAPP systems have been included. Interestingly, most of CAPPs developed so far have not adequately addressed the problem of dimensional control on the workpiece. The research works in this direction are still few. Even though some attempts [33, 34] have been made to analyse dimensions of the part by means of computers, the systems developed are not related directly to process planning. Other CAPP researchers such as Weill [35], Sack[20], Chang, Wysk [36], and Davies [37] have realised this problem, but so far no studies have been reported that base process sequencing on dimensions and tolerances of the part.

On the fixture design side, the research may be classified into 3 broad categories: (1) the development of new methods of fixturing, (2) computerised conventional fixture design, and (3) computerised modular fixture design. In the first category, the research is directed at finding new methods for holding workpieces. An example of this kind of research is the fluidized bed fixture developed by Gandhi and Thompson [38]. The work that belongs to the second category is concerned with the design, selection and assembling of the conventional jig or fixturing elements such as locating pins, buttons, screw clamps, strap clamps, etc. Examples of work in this category are: the

'Programmable Comformable Clamps' developed by Cutkosky et al [39] for clamping turbine blade; the computer package for designing jigs and fixtures for a Flexible Manufacturing System (FMS) developed by Drake [40]; and the work reported by Berry [41] on the implementation of CAD/CAM to fixture design. Other research contributions, based on an AI approach, that fall into this category, include the work of; Miller and Hannam [42], Nee et al [43], Anglert and Wright [44], Lim and Knight [45], Pham et al [46], Pham and Lazaro [47], and Darvishi and Gill [48]. The third category is concerned with the design of modular fixtures; the outstanding work which could be considered as the prototype of AFD was developed by Markus et al [49] in Hungary. In this computer package, an AI technique was implemented through the use of Prolog. The program can generate automatically the towers and supports to suit the identified points for locators and other fixturing elements. This work started a new area of computer application, and it inspired manufacturing researchers, including those mentioned above, to turn to this research direction. Also included in this category are the modular fixturing system of Woodward and Graham [50], the design methodology based on the AI technique proposed by Gandhi and Thompson [51], and Ngoi's system [52] for assembling of modular fixturing elements.

There is other research work which is not bound by any of the above categories, because it is concerned with some special aspects of fixture design. The work along this line includes that contributed by Chou et al [53] on the application of the classic screw theory to identify the locating and clamping points, by Lee and Haynes [54] on finite-element analysis of flexible fixturing system, and by Halevi and Weill[55] on the application of tolerance analysis to fixturing design.

Trappy and Liu [56] have recently published a literature review on the computerised design of fixture; the conclusion is at present the fully automatic fixture design has not been completely developed. Furthermore, in order to realise such system, a theoretical base for analysing the general and basic principles of the workpiece-fixturing relationship needs to be developed.

1.3 Problems in developing CAPP and AFD systems

The problems encountered by researchers working on CAPP and AFD can be listed as follows:

(a) Form of computer input:

Most of the systems developed so far depend on extensive interaction between user and computer. That means the description of the features on a part component must be first manually extracted from the design, and then input in to the computer. This inefficient method has led to the use of solid models to represent the part geometry in the computer. Although much progress in solid modelling technology has been made in recent years, further development is required before it can be fully utilised in process planning [57].

(b) Extraction of features from a CAD system:

This problem is related to the first one. Because a solid model does not provide the data that can be used by a CAPP system directly, a means has to be devised to extract the required information from the CAD database and store it in a usable form [58]. Research in this area is still in an early stage but together with solid modelling it forms the realm of feature recognition.

(c) The manufacturing information on a solid model:

A solid model of a part can only represent the geometrical shape of the part. In process planning, not only the features on the model must be extracted from the part model, but also the information about manufacturing specifications must be supplied by some other means to the system. This has led to the idea of attaching manufacturing information to the features at the design stage; the design representation of this nature is usually referred to as 'design by features', or 'design with features'. However such a design representation has not yet been adequately developed for machined part designs; although, substantial progress has been made in relation to casting designs in the United States [60].

(d) Tolerance control:

Although tolerance control is a basic issue in metal machining, most of the CAPP systems do not take it into account. This is probably because the recent advancement in machine-tool technology has made available machine-tools capable of producing dimensions with a far closer tolerance than in the past. This suggests that the use of advanced machine-tools overcomes the problems of tolerance stacking. But this is only true when only one setup is required for machining the whole workpiece. In practice, a workpiece often requires different setups for different operations and hence tolerance control remains a basic issue.

Trappy, Liu [56] Alting and Zhang [32], all realise that this aspect of control has been omitted from most of the research on both CAPP and AFD.

1.4 Objectives and scope of the project

Although CAPP systems have been researched for more than 20 years, the results are still short of the requirements of industry [32]. One of the obstacles is that the basic practical principles of process planning have been mostly abandoned in the existing CAPP systems. Although AI is used, it is used mainly for supporting the system, eg, for recognising a machining feature, rather than encapsulate the manufacturing knowledge. In those AI-based systems that do incorporate the manufacturing knowledge, the knowledge has been in the form of technical information extracted mainly from books and publications which neglect the basic technological principles completely.

The work reported here is, therefore, directed at demonstrating the important role dimensional relationships between machined features have in process planning and fixture design.

The general objective of the research is to investigate the feasibility of using the principles of workpiece control as a guide to generating the machining sequence. The thesis of this research is that automatic planning of machining sequences can be achieved by applying practical basic principles.

In order to demonstrate the idea, a CAPP system with the following characteristics was to be developed:

(1) The system is for prismatic parts with only three types of machining features, namely; step, slot, and plane surface.

(2) The machining operations are confined to milling.

(3) The system is capable of creating the machining sequence automatically.

(4) The system is equipped with a tolerance control technique: the tolerance chart.

(5) In connection with fixture design, the system is able to provide the fixture designers with information such as the appropriate

locating surfaces (in 3-2-1 location system) on the workpiece for each machining operation. It is not intended to consider the design of the fixture body.

(6) In addition to the above characteristics, the system is implemented on a PC.

1.5 Progrmming technique

While the sequencing facilities in most existing CAPP systems are based on the changes of the workpiece geometry alone, the system developed here uses the two types of workpiece control: dimensional and geometric, as a basis for planning the sequence of machining.

Although at present the expert system approach has been widely adopted in CAPP systems, the real expert system for process planning has not yet been realised. It will appear that the best method of developing an expert system requires the actual expert in a particular problem domain to undertake the development himself. This requires time for him to study the principles and logical concepts of expert systems. Even so after an expert system has been developed, it still requires a real expert to test, modify and maintain the system. These are the obstacles to a successful expert system in this area of research. On the other hand, a system based on the conventional programming technique, whilst it does not provide the same level of flexibility as an expert system, requires less time to develop and hence is suitable for testing the feasibility of an approach to a problem which requires a procedural steps for solution. The results of this could help reduce the work of a real expert in developing an expert system, because the expert system can be confined to the narrower area which requires the practical skill and experience.

Because mechanical control is more concerned with the experience of a tool designer in designing or choosing fixturing elements, this aspect of workpiece control is more suitable for an expert system than is dimensional and geometric control. This project, which demonstrates the implementation of the latter, therefore uses the conventional programming technique.

1.6 Computer-aided process planning and fixture design system (CAPPFD)

Since there is no intention to research in areas relating to solid modelling, a simple part model representation has been adopted in the system developed. This representation limits the capability of the system to prismatic parts having edges parallel to x-, y-, or z-axis, and to two-dimensional machined features. The system is capable of generating the machining sequence for three types of machined feature, namely, plane surfaces, steps and slots.

In executing the program, CAPPFD starts from reading the part model data from a data file, executing the input routine for other data, sequencing the machining operations, designing the location systems, and finally drawing the tolerance charts for all process dimensions.

1.7 Conclusion

Process planning and fixture design are closely inter-related. A processing sequence can not be planned properly without considering the location systems; likewise, an economic fixture design can only be designed when the machining sequence is available. The objective of this research project is to demonstrate how this desirable point can be achieved by making use of the dimensional relationships from the finished part drawings.

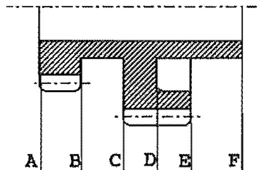
2. TOLERANCE CHART TECHNIQUE

Since the aim of process planning is to achieve the design specifications, it is essential that the process plan be checked for its practicality: in this respect a tolerance chart is an indispensable tool. However, the manual procedures available for tolerance charting are not appropriate for computer programming, therefore a new method of tolerance charting was developed during the course of this research. The method developed not only facilitates the computerised charting, but also helps reduce time and errors in manual charting. This chapter introduces the background of the tolerance chart, and then details the development of the new charting technique.

2.1 Tolerance charts

A tolerance chart is a graphical representation of a machining sequence on a part. It shows dimensions and tolerances for the machining cuts and for the stock to be removed at all steps of manufacture. It is an analysis tool used by the process planner for assessing the feasibility of a machining sequence prior to the actual machining operations. It is also a means of communication between the process engineers and product designers. The comprehensive summaries of its uses are listed in Ref [12, 61, 62]. Other specific uses of the tolerance chart include:

(a) By coordinating with quality control charts, it can be used to define the relationship between dimensional analysis and dimensional control [63].



1 CUT NO.	2 OPER. NO.	3 FACE CUT	4 MACHINE	5 WORKING DIM. BASIC	6 WORKING DIM. +/-TOL.	7 STOCK REMOVAL BASIC	8 STOCK REMOVAL +/-TOL.
0		A			0		
1		B		42.17	0.762	stock	
2		C		5.68	0.381	stock	
3		E		29.39	0.761	stock	
4	1	F1	Au.lathe	39.73	0.381	2.44	1.143
5	"	E1	"	7.46	0.076	2.80	1.600
6	2	A1	Au.lathe	30.77	0.076	1.50	0.533
7	"	C1	"	24.05	0.076	2.54	0.914
8	"	C2	"	21.65	0.076	2.40	0.152
9	3	A2	I.D Grd.	30.64	0.051	0.13	0.127
10	4	F2	S. Grd.	37.95	0.051	0.15	0.178
11	14	C3	Turret L.	19.25	0.076	2.40	0.152
12	"	A3	"	8.99	0.076	2.40	0.203
13	"	B	"	2.20	0.076	solid cut	
14	15	F3	Turret L.	24.16	0.051	2.40	0.229
15	"	D	"	6.80	0.102	solid cut	
16	16	C4	I.D Grd.	19.05	0.051	0.20	0.127
17	"	A4	"	8.94	0.025	0.25	0.228
18	26	F4	S. Grd.	32.70	0.102	0.20	0.305
19	27	A5	S. Grd.	32.50	0.076	0.20	0.178
				BLUEPRINT		RESULTANTS	
				19.05	0.254	19.05	0.051
				6.60	0.254	6.60	0.229
				8.74	0.254	8.74	0.203
				2.40	0.254	2.40	0.203
				32.50	0.254	32.50	0.076

NOTES: All dimensions are in millimetres.

surface being cut

gauging surface

locating surface

Fig.2.1: Tolerance chart for producing a gear [66].

(b) It provides a basis for solving product assembly problems [64].

(c) It is a means for formulating a mathematical relationship among processing tolerances which is essential in the optimum tolerance allocation [65].

Since the early 1950s, there have been reports on the uses of tolerance charts, in both aircraft and automobile industries [64, 66]. However, the technique has not been widely practised among other industries. This is because the principles of tolerance charting requires time to learn, and the charting itself is a time consuming and error-prone process. Therefore many procedures have been proposed to simplify the technique; these include those proposed by Mooney [67], Gadzala [61], Johnson [68], and Wade [69].

The idea of computerised tolerance charting first appeared in the Computer Managed Process Planning (CMPP) system developed by the United Technologies Research Center [20]. Then, Ahuluwalia and Karolin [70] developed the CATC - a computer aided tolerance control system based on a tolerance chart. On the charting algorithm development side, Xiaoqing and Davies [71] developed a tree-chain method for tolerance chart calculations; Irani et al [65] developed an algorithm based on graphs theory to identify the machining cuts that contribute to the finished dimensions. A new method for tolerance chart calculations was developed for this project based on 'rooted-tree' directed graphs; it is reported by Whybrew et al [72, 73, 74]. A copy of Ref [72] is given in Appendix A.

2.2 Development of tolerance charting technique using rooted-tree graphs

Fig. 2.1 shows a tolerance chart for producing a gear. (All dimensions and tolerances are converted from inches in Ref [66].) In this chart, an arrow points to the surface being machined, and a dot denotes a locating surface or the surface from which the dimension of the corresponding cut is measured. From now on, a surface identified by this dot is simply called a locating surface (or a locating face). From each vertical face on the part sketch there is a line drawn downwards throughout the length of the chart; this line represents a surface and is labelled with a capital letter. There are columns for: the basic dimensions resulting from the machining cuts, which are normally called 'working dimensions'; the machining tolerances; the stock removal dimensions; the tolerances on stock removal dimensions; the drawing dimensions and tolerances; and the resultant dimensions and tolerances. Other columns are used for recording types of machine, operation numbers, and letters identifying the surfaces resulting from the cuts. Some other tolerance charts provide an extra column for balance dimensions: the dimensions which are the results of two or more cuts. However, the balance dimensions are not shown in this chart; the reason for this will be clear when the technique has been fully explained. All the tolerances are expressed in the equally bilateral system. Because the tolerance chart is concerned mainly with the tolerances on length dimensions, the details of diametral or traversed dimensions are omitted from this analysis. It should be noted that the stock dimensions are also included in the chart as the working dimensions.

To construct a tolerance chart for a machined part, first the basic information is filled in the prepared chart form. This basic information includes the drawing specifications of the part, the sequence of machining, the processing tolerance and the amount of stock removal at each cut, and the type of machine for each operation. After this the calculations are made to find the working dimensions and tolerance stacks on the stock removals and on the resultant dimensions.

In the conventional tolerance chart [12], a surface being cut is identified by a single capital letter as mentioned before. Actually, the surface before and the surface after a machining cut are not the same surfaces; therefore, they should not be identified by the same notation. The present technique has introduced a numerical suffix to a newly machined face. With this system, the essence of the machining sequence in Fig. 2.1 can be listed as follows:

Line # 1: face F is defined relative to locating face A

Line # 2: face C is defined relative to face A

Line # 3: face E is defined relative to face C

Line # 4: face F1 is defined relative to face A

Line # 5: face E1 is defined relative to face F1

Line # 6: face A1 is defined relative to face E1

Line # 7: face C1 is defined relative to face E1

Line # 8: face C2 is defined relative to face E1

Line # 9: face A2 is defined relative to face E1

Line # 10: face F2 is defined relative to face A2

Line # 11: face C3 is defined relative to face E1

Line # 12: face A3 is defined relative to face C3

Line # 13: face B is defined relative to face C3

Line # 14: face F3 is defined relative to face C3

Line # 15: face D is defined relative to face C3

Line # 16: face C4 is defined relative to face E1

Line # 17: face A4 is defined relative to face C4

Line # 18: face F4 is defined relative to face A4

Line # 19: face A5 is defined relative to face F4

This can be summarized diagrammatically in the rooted-tree graph as shown in Fig. 2.2 where each node represents a locating surface or a machined surface or both, and an arrow points to a machined surface. The working dimension is represented in this diagram as a link between two nodes, and identified by a line number (or a cut number).

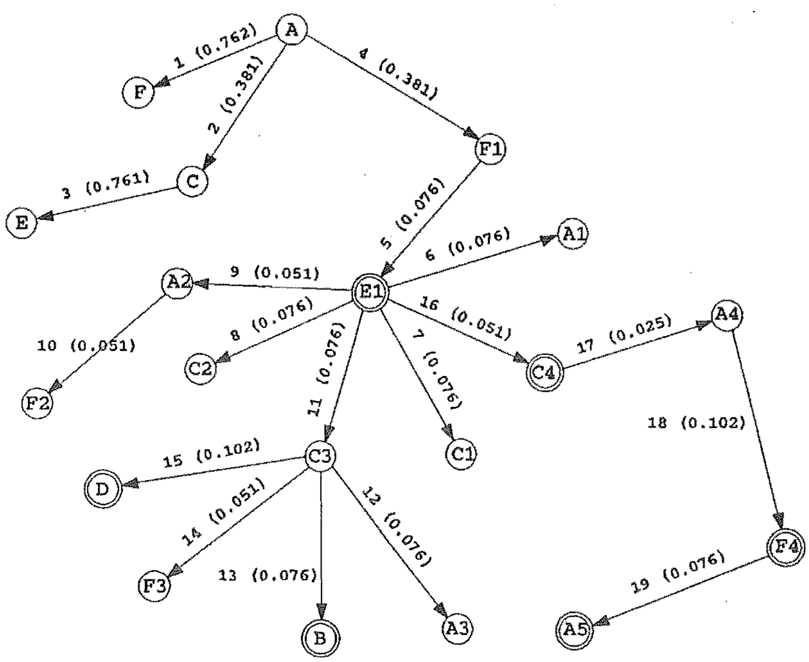


Fig.2.2: The rooted-tree diagram for producing a gear.

In this graph, the path from any one node to another defines the cuts that contribute to the distance -- dimension and tolerance -- between the two surfaces denoted by the nodes. For example, the resultant dimension between B and C4 is the result of cuts 11, 13, and 16; and its tolerance is the sum of these machining tolerances. Or, the tolerance stack on stock removal at cut 7 is the sum of the tolerances of the links in the path from node C1 to node C. Therefore, by using the rooted-tree diagram, the cuts that give rise to any pair of surfaces can be readily identified.

The rooted-tree graph method provides a convenient means to calculate the tolerance stacks, on either the stock removal dimensions, or on the resultants; it can also be used to calculate the working dimensions in most practical cases as explained in Ref [72, 73]. However, in some uncommon cases where locating surfaces for machining a surface are changed often in the course of machining, the technique is not able to derive some working dimensions. Therefore a study was made on the fundamental aspects of the working dimensions. It was found that any working dimension is the result of adding or subtracting the drawing dimension with the stock removal dimension(s). This is the basic procedure in manual charting, and it is adopted here.

2.3 A method for calculating working dimensions

All procedures for deriving the working dimensions are basically the same in concept: working backwards from the finished part dimensions to the raw stock dimensions. The method adopted here, too, starts from a drawing dimension corresponding to the unknown working dimension; add and/or subtract the metal to or from the dimension whenever there is a cut made on the surfaces that bound the drawing dimension. Fig.2.3 illustrates this method. The working dimensions of cut 4, 5 and 6 can be calculated as follows:

cut 4 = (ab + m6 + m7),

cut 5 = (cd - m8 + m9), and

cut 6 = (ef + m8);

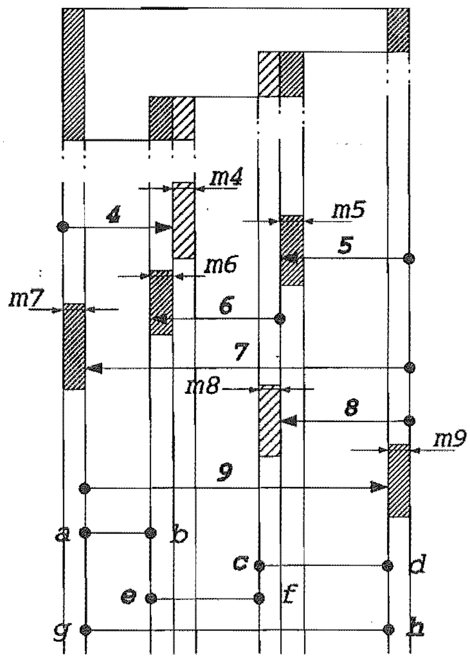


Fig.1.3: Showing the method of calculating the working dimensions.

where ab, cd, and ef are the drawing dimensions; and m6, m7, m8, and m9 are the metal removal dimensions at cuts 6, 7, 8, and 9 respectively.

2.4 Manual tolerance chart calculations

Now, the rooted-tree graph technique will be applied to the tolerance chart in Fig. 2.1. First, assume that all relevant information has been filled in the chart; the values to be calculated are in columns 5, 8, and in the resultant column. Then, the rooted-tree graph (in Fig. 2.2) is drawn from the sequence of machining in the chart. Also, attached to the links in the diagram are the line (or cut) numbers, the machining tolerances (in parentheses).

(a) **Calculations of tolerance stacks:**

As mentioned earlier, the tolerance stacks on the stock removal and on the resultant dimensions are calculated by summing up the machining tolerances of the links in the relevant paths. Therefore, to calculate the tolerance stack on the stock removal at cut 6, first, from the graph, pick up the path with the starting node A1 and the ending node A, or vice versa; then, sum up the tolerances on the links:

$$0.076 + 0.076 + 0.381 = \underline{0.533} \text{ mm.}$$

Note that A1 and A are the surfaces that bound the stock removal dimension at cut 6, and the numerical suffixes of the two surfaces are different by 1.

The same procedure is applied to the tolerance stacks on the resultant dimensions. The only difference is the starting and ending nodes are defined by the drawing dimensions instead of the stock removal dimensions. For example, the tolerance stack on the drawing dimension between surfaces C4 and D is equal to the sum of tolerances on cuts 16, 11, and 15:

$$0.051 + 0.076 + 0.102 = \underline{0.229} \text{ mm.}$$

Surfaces C4 and D are both the last machined surfaces which give the drawing dimensions. In Fig.2.2, all the last machined nodes are surrounded by two circles to make them different from the others so that they can be identified easily.

(b) Calculations of working dimensions:

To calculate the working dimensions, consider the tolerance chart in Fig.2.1, trace up along the two surfaces from the drawing dimension corresponds to the working dimension in question, and add or subtract, as the case may be, the drawing dimension with the amount of stock removal at each cut that encounters the surfaces. The conditions to add or subtract the working dimension with the stock removal can be summarized in two decision tables, shown in Fig.2.4. (A brief discussion of decision tables is given in Appendix B.) In this figure, d1 and d2 are the lower and the upper ends of a drawing dimension; lo[c] is the locating surface for a cut, which is made on the surface below the unknown working dimension; and 'SIGN' is a variable identifying if a particular cut shortens or lengthens the distance between two surfaces. If a cut results in a shorter distance -- that is the distance between two surfaces after the cut is shorter than before the cut, SIGN is -1; otherwise, +1. With the rules in the tables, the working dimensions of cuts 2, and 3 can be calculated as follows:

cut 2:

8.74 - 0.20 - 2.40 - 2.40 - 2.54 + 0.20 + 0.25 + 2.40 + 0.13 + 1.50 = <u>5.68</u> mm.

cut 3:

19.05 + 2.80 + 0.20 + 2.4 + 2.4 + 2.54 = <u>29.39</u> mm.

(c) Notes on stock dimensions, tolerances and solid cuts:

If a machined part is machined from a casting or stock with specific sizes, its dimensions are included at the top part of the chart. Since these dimensions have to be treated like working dimensions, an arrowhead and a dot are required for each of them. Each of the dimensioned surface pointed

condition stub	condition entry			
lo[c] > d1	0	0	1	1
lo[c] < d1	1	1	n	n
SIGN = +1	1	0	1	0
action stub	action entry			
ADD	X			X
SUBTRACT		X	X	

(a) for the lower end of
a drawing dimension

condition stub	condition entry			
lo[c] > d2	0	0	1	1
lo[c] < d2	1	1	n	n
SIGN = +1	1	0	1	0
action stub	action entry			
ADD		X	X	
SUBTRACT	X			X

(b) for the upper end of
a drawing dimension

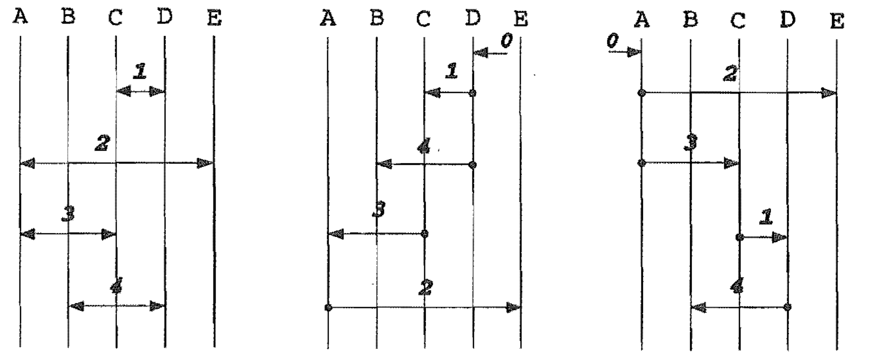
Fig.2.4: Rules for adding or subtracting the working dimension with a metal removal dimension.

to by the arrowhead is deemed to have been machined before. The rules adopted for assigning the directions of arrowheads to stock dimensions are:

(1) the arrowhead of line 0 can point to any surface;

(2) then, that surface is the first reference from which the subsequent stock dimensions are measured;

(3) the subsequent stock dimensions will never be measured from any surface that has not been previously pointed to by an arrowhead of a dimension.



(a) stock dimensions (b) working dimensions (c) working dimensions

Fig.2.5: The method for converting the stock dimensions to the working dimensions.

Fig.2.5 shows two examples of converting stock dimensions to working dimensions. The stock dimensions are given in (a). If the arrowhead of line 0 is assigned to surface D, then the stock dimensions can be represented as in (b); but, if surface A is chosen to be the starting surface, then the result is (c). Note that the changes in positions of the working dimensions depend on the surface chosen for line 0.

In a tolerance chart, the word 'solid' is inserted to the first cut made on a surface in the column of stock removal dimensions. This is a normal practice when the part is machined from a bar stock, and no stock dimension is given. This practice still applies to the case where stock dimensions are treated as working dimensions; but the word such as 'stock' or 'casting' or 'forging' is used instead of 'solid'. And the machining tolerances of these working dimensions are the tolerances on the stock dimensions.

2.5 Computer program for tolerance charting

Fig.2.6 shows the macro-flow chart of the computer program for tolerance charting. This program is then combined with the program for sequencing the machining operations and locating the workpiece, which will be explained in the subsequent chapters, to become a fully computerised process planning and fixture design program.

In box 1, the distances between surfaces(A, B, C, etc) are calculated from drawing dimensions and stored in a 2D-array. This distance matrix facilitates the calculations of working and resultant dimensions. In box 2 all working dimensions are calculated. Before a tolerance stack on a stock removal dimension can be calculated, a path containing the cut numbers is created between the two faces of the metal removal, and then the tolerance stack is calculated. This is shown in boxes 3 and 4. The same procedure is also applied to calculate both the tolerances (boxes 5 and 6) and the dimensions of the resultants (boxes 7 and 8). These resultant dimensions can, in fact, be copied directly from the drawing dimensions; however, in this program, as a check, they are calculated back from the known working dimensions. In box 9 the results are printed.

Note that the program does not store all the paths from the cut faces to the root; it creates the path when required; after the path has been used the memory of it is not retained.

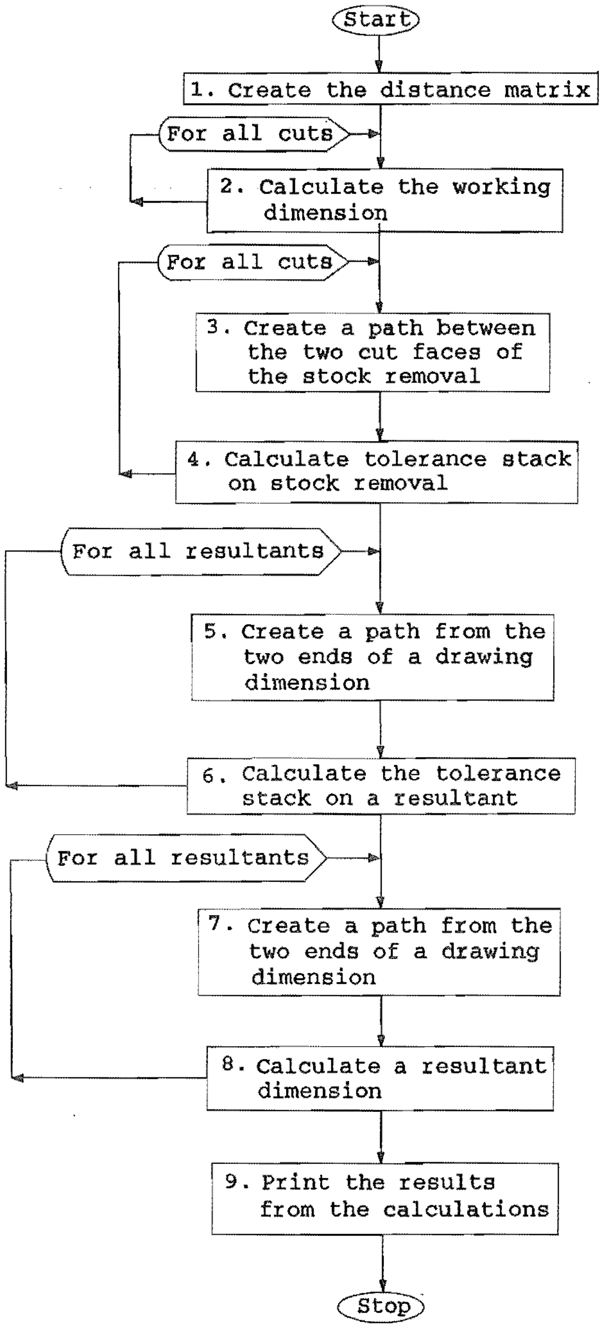


Fig.2.6: Macro flow-chart for tolerance chart calculations.

2.6 Conclusion

The details of tolerance charting with the new technique have been explained. A computer program, based on this technique, was developed, tested and found to work well with data from various publications [61-63, 66-69, 75] (some of the test results are shown in Appendix C). When used in manual charting, it was found that the technique could reduce the time required, and the number of errors made. It could also be used as a supplementary tool to other charting techniques such as Wade's and Gadzala's methods. For a comparison, the reproduction of the latter is given in Appendix D.

3. SYSTEM STRUCTURE

The Computer-Aided Process Planning and Fixture Design (CAPPFD) system developed in this project is written in C and implemented on a PC, with a base memory of 640 K bytes, under the DOS operating system. In this chapter the overview of CAPPFD is presented. This includes the types and general characteristics of the features that the system can handle, and the program modules that constitute the system.

3.1 Machined features for CAPPFD

Although the system is designed to work on a prismatic part, which is a three-dimensional object, the machined features on the part are confined to two-dimensional ones. Here, the two-dimensional feature may be defined as a machined feature comprised of only flat surfaces; each of them being parallel to one of the principal planes. Therefore, the feature can be presented graphically and dimensionally in two orthogonal projection views. The common machined features that fall into this category are flat surfaces, steps, and slots; examples of these are shown in Fig. 3.1. The features chosen to work with are limited by the workpiece model representation inside the computer (which will be described in the next chapter). But these features are sufficiently general to form a basis to demonstrate the concept used for computerized process planning and fixture design.

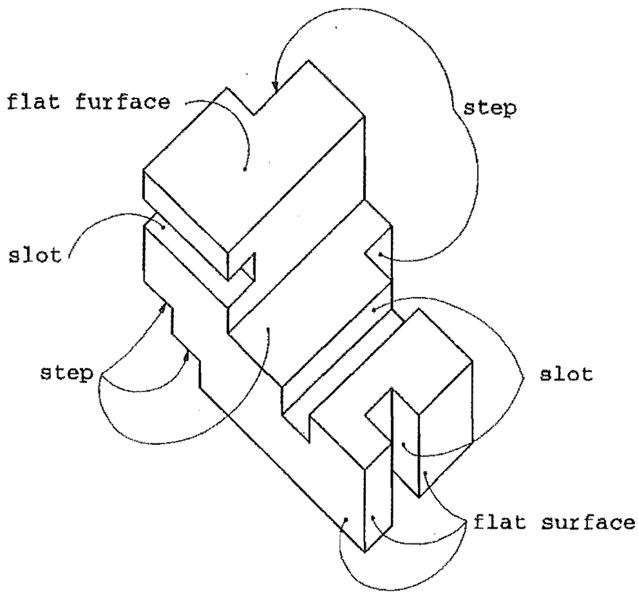


Fig.3.1: Typical machined features for CAPPFD.

3.2 Structure of CAPPFD

CAPPFD consists of 208 sub-programs which are grouped into six modules (or files) as follows:

(1) **Input and editing module:** contains the main part of the program, and the data input and editing routines.

(2) **Sequencing module:** contains the routines (or sub-programs) for sequencing the machining operations.

(3) **Locating module:** contains the routines for selecting an appropriate 3-2-1 location system for each operation.

(4) **Tolerance chart module:** contains the routines for producing tolerance charts.

(5) **Support Module:** contains the routines for the following two main functions:

• producing the drawings of the part on the screen or on the printer, with or without the locating symbols; and

• extracting the coordinates of the surfaces on the part and storing them in a set of linked lists.

(6) **Utilities module:** contains two sets of routines of which the first contains the general purpose sub-programs that are used by almost every module, eg. the routines for allocating and freeing the dynamic memories, and the second is concerned with modifying the workpiece model representation and storing it in a dummy data file.

Fig.3.2 shows the inter-relationships among the modules mentioned above. The data files are also included here to complete the overall structure of the system. These data are of two types: the first is the model representation data, and the second is, the so called, 'production data' -- eg. depths of cuts, number of cuts, processing tolerances, etc.

3.3 CAPPFD flowchart

Fig.3.3 shows the simplified flowchart of the CAPPFD system. Also included in the figure are types of data and program modules required at various stages of execution; the data are in dotted line boxes, and the program modules, in full line boxes.

The system starts with the input of data which consists of two steps: in the first step, the input and editing module reads the part model

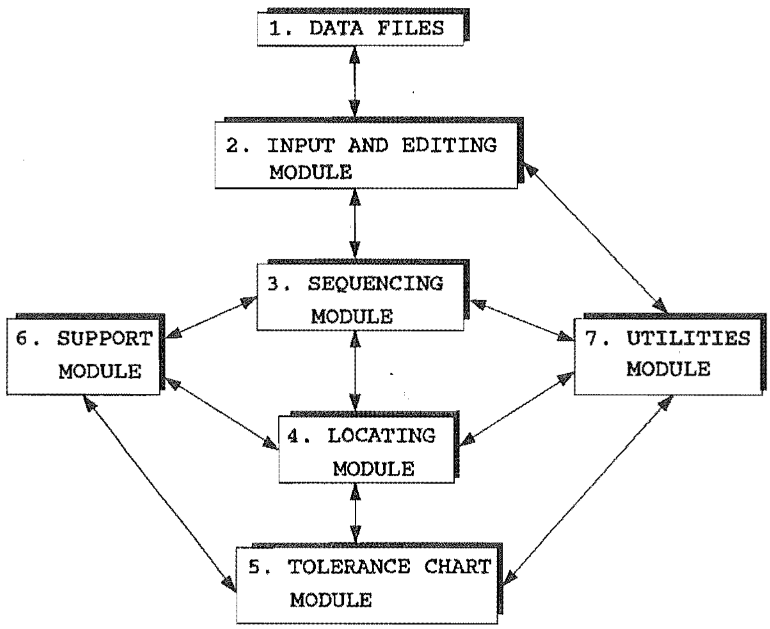


Fig.3.2: Structure of the CAPPFD system.

representation data, which have already been stored in a data file; this is followed by the second step: the input of the production data. Two options are provided for inputting the production data: the user either interactively inputs the data into the system, or let the system read the data from a data file, which requires the data be previously stored in a data file.

After the data input session is completed, the sequencing module starts to sequence the machining operations; this requires data such as drawing tolerances, the surface numbers that constitute each feature, etc. The result of this execution is the machining sequence.

Then, the locating module determines the 3-2-1 location system for machining each feature. The same location system is used for all cuts that are required to produce a particular feature. During this stage of execution, the system displays all the location systems on the monitor screen, and if required, the outputs can also be printed out on a line printer.

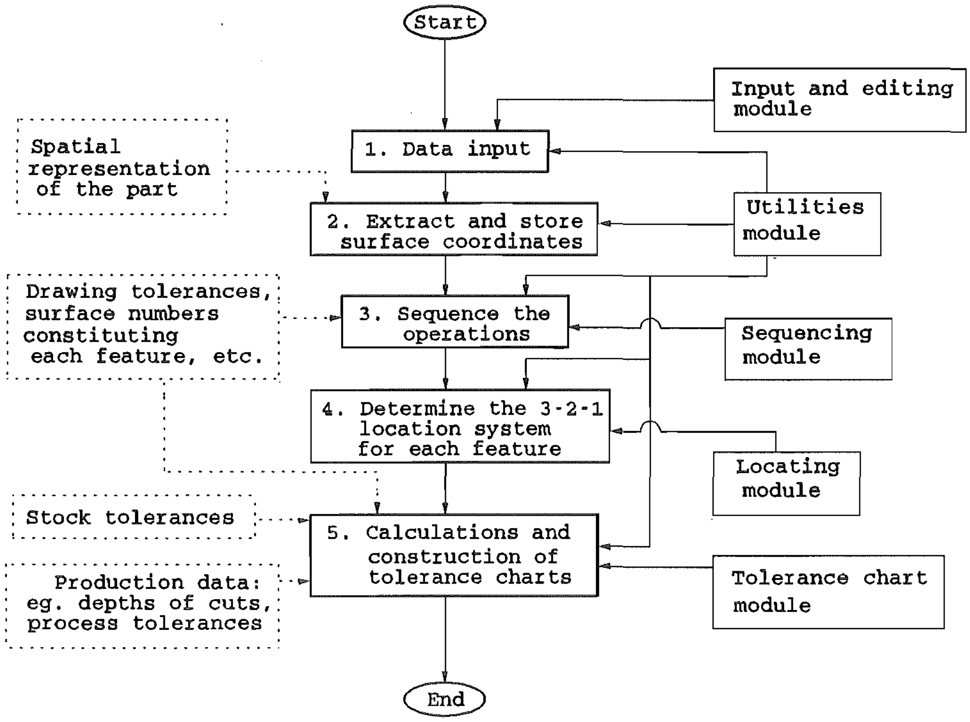


Fig.3.3: Macro-flowchart of the CAPPFD system.

In the final step, the system performs tolerance chart calculations and draws the tolerance charts. Three tolerance charts are drawn on the screen. The user can also print the screen outputs on the printer if required.

The user may modify the processing tolerances by re-running the system and using the editing routines to modify the data. The sequence of the operations resulting from the system cannot be modified. This is required to preserve the merits of the system: the system tries to achieve the best combination of dimensional control and geometric control. However, modifications of the sequence could be made indirectly by altering design dimensions or by modifying the values of design tolerances.

3.4 Conclusion

The CAPPFD system contains 6 program modules, namely; the input and editing module, the sequencing module, the locating module, the tolerance chart module, the support module, and the utilities module. It is capable of sequencing three types of machined feature, ie, plane surfaces, steps and slots.

This chapter serves as an introduction to the details that follow in the subsequent chapters: chapter 4 discusses the data structures, and the input and editing module; chapter 5 explains how the machining operations are sequenced; chapter 6 discusses the details of the locating module and the algorithm for modifying the workpiece model representation; chapter 7 describes how the tolerance chart program is integrated in the main package; chapter 8 shows two examples of the implementation of the system, and chapter 9 is the conclusion of this research project.

4. DATA: STORAGE, INPUT AND OUTPUT

CAPPFD stores all geometric data of a machined part in a three-dimensional array, the amount of memory for which is allocated dynamically, and depends on the complexity of the part. This simple technique for solid modelling was developed by Ngoi [52]. However, the part model does not incorporate other essential information such as the identification of surfaces that bound a feature, the tolerances on dimensions, or the cutting conditions required for each feature. This information is regarded roughly as the 'production data', and is stored separately. This chapter discusses the structures and the input/output of CAPPFD data.

Although the part model is a 3D-array and any array operations can be performed on it, some of the object elements of this array represent different conditions from the others. This is the essence of the technique; it is described in the following section.

4.1 Spatial representation technique

The spatial representation technique is a method for representing the geometry of a part inside the computer which makes use of a series of two dimensional arrays to define the part geometry. To illustrate the concept of the technique, consider the bracket in Fig.4.1. If a set of orthogonal x-y-z axes is laid on the part as shown in Fig.4.2(a), and a series of planes parallel to the three principal planes are inserted through the part, the existence of the material between two adjacent planes can be represented by a two dimensional array. Fig.4.2(b) shows two orthogonal views of the part with horizontal and vertical planes at various x, y and z coordinates. The spatial representation of the bracket along z-axis is shown in Fig.4.2(c). The numbers in the first row, except the first one, denote the x-coordinates; the numbers in the first column, except the first one, denote the y-coordinates. The number in the first row and the first column of each array denotes the z-coordinate. The other numbers, non-zero and zero numbers, denote respectively the existence and non-existence of the material between one plane and the next lower plane. Therefore, in the array at z=49.0, the zero defined by row 1 and column 4, indicates that there is no material of the part from x=70.0 to x=60.0, from y=20.0 to y=0.0, and from z=49.0 to z=39.0 mm; while the number 99 in the array at z=39.0 in row 1 and column 4 indicates the existence of the part material from x=70.0 to x=60.0, from y=20.0 to y=0.0 , and from z=39.0 to z=35.0 mm.

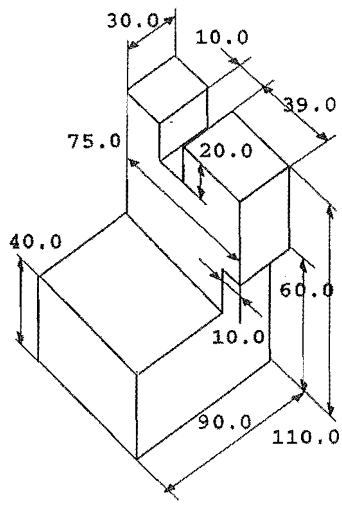
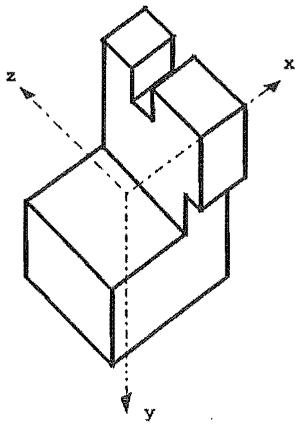


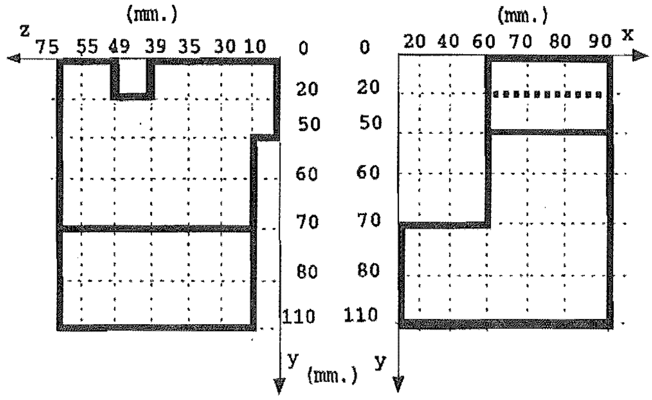
Fig.4.1: A bracket (in mm.)

The decimal point numbers are used because all array elements are required be of the same data type. However, in Fig.4.2 all decimal points are omitted for clarity.

To input the spatial representation of a part into the computer, the drawings of the part are first converted to a form as in Fig.4.2(b), from which a series of two dimensional arrays of numbers can be readily constructed. Then the numbers are arranged in a data file for the computer to read. At present this procedure is done manually.



(a)



Note: The thin dotted lines represent the planes.

(b)

Plane z = 0:

0	20	40	60	70	80	90
20	0	0	0	0	0	0
50	0	0	0	0	0	0
60	0	0	0	0	0	0
70	0	0	0	0	0	0
80	0	0	0	0	0	0
110	0	0	0	0	0	0

Plane z = 10:

10	20	40	60	70	80	90
20	0	0	0	99	99	99
50	0	0	0	99	99	99
60	0	0	0	0	0	0
70	0	0	0	0	0	0
80	0	0	0	0	0	0
110	0	0	0	0	0	0

Plane z = 30:

30	20	40	60	70	80	90
20	0	0	0	99	99	99
50	0	0	0	99	99	99
60	0	0	0	99	99	99
70	0	0	0	99	99	99
80	99	99	99	99	99	99
110	99	99	99	99	99	99

Plane z = 35:

35	20	40	60	70	80	90
20	0	0	0	99	99	99
50	0	0	0	99	99	99
60	0	0	0	99	99	99
70	0	0	0	99	99	99
80	99	99	99	99	99	99
110	99	99	99	99	99	99

Plane z = 39:

39	20	40	60	70	80	90
20	0	0	0	99	99	99
50	0	0	0	99	99	99
60	0	0	0	99	99	99
70	0	0	0	99	99	99
80	99	99	99	99	99	99
110	99	99	99	99	99	99

Plane z = 49:

49	20	40	60	70	80	90
20	0	0	0	0	0	0
50	0	0	0	99	99	99
60	0	0	0	99	99	99
70	0	0	0	99	99	99
80	99	99	99	99	99	99
110	99	99	99	99	99	99

Plane z = 55:

55	20	40	60	70	80	90
20	0	0	0	99	99	99
50	0	0	0	99	99	99
60	0	0	0	99	99	99
70	0	0	0	99	99	99
80	99	99	99	99	99	99
110	99	99	99	99	99	99

Plane z = 75:

75	20	40	60	70	80	90
20	0	0	0	99	99	99
50	0	0	0	99	99	99
60	0	0	0	99	99	99
70	0	0	0	99	99	99
80	99	99	99	99	99	99
110	99	99	99	99	99	99

(c)

Fig.4.2: Matrix Spatial representation technique.

4.2 Data structure for surface coordinates

The series of two-dimensional arrays of the spatial representation are stored in the computer in a three dimensional array, $solid_{kji}$; it is then used as the part model from which the surface coordinates are extracted. The subscripts i, j and k are the indexes along x, y and z axes respectively.

The coordinates (x, y, z) of all corner points of each surface on the machined part are stored in a linked list as shown in Fig.4.3. By using this type of data structure, the maximum number of points may be stored for a surface is limited only by the amount of computer memory. There are three sets of linked lists. The first set stores all the coordinates of the surfaces parallel to xz-plane; the second set stores those of the surfaces parallel to yz-plane, and the last set, of the surfaces parallel to xy-plane. The addresses of the three sets of linked lists are stored in three two-dimensional arrays of pointers: xzptr[i][j], yzptr[i][j] and xyptr[i][j].

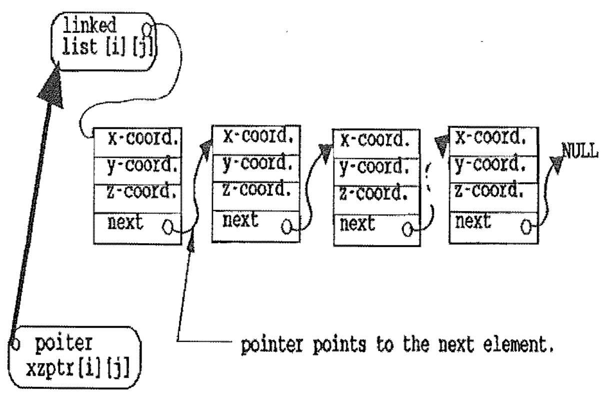


Fig.4.3: A linked list.

These three arrays can be considered as the sets of pointers pointing to the lists of data points corresponding to the surfaces at various levels on the part model. For example, xzptr[i][j] points to the list belonging to surface j on level i. CAPPFD can handle up to 20 levels, along each principal axis, with up to 5 surfaces on each level. While extracting the surface coordinates, the system also attaches to each surface an integer identifying the direction of its normal out of the part: +1 denotes a surface facing away from the origin, and -1, facing towards the origin. This information is used in all stages of execution -- sequencing, locating, and charting; it is stored in the following arrays: xzd[i][j], yzd[i][j] and xyd[i][j], corresponding to the three sets of linked lists mentioned above.

4.3 Surface coordinate extraction

The coordinates-extracting routines, in the input and editing module, starts to execute after the geometric data of the machined part has been stored in $solid_{kji}$. The basic idea of the extracting algorithm is to search for the corner points of the solid material on every layer of the model, $solid_{kji}$. Here, the layer means a strip of material in the model represented by an array of numbers on a plane perpendicular to y-axis. From the top to the bottom, the program will search layer by layer. For example, in Fig.4.2(b), the first search is on the layer at j=1, and the last search is on the layer at j=6 (layer at j=0 contains only coordinates of x- and z-axes).

The general pattern of movement in searching for a corner point is shown in Fig.4.4. An anti-clockwise movement is made along the edge of a surface. Once a point is found the position of the point, relative to x and z

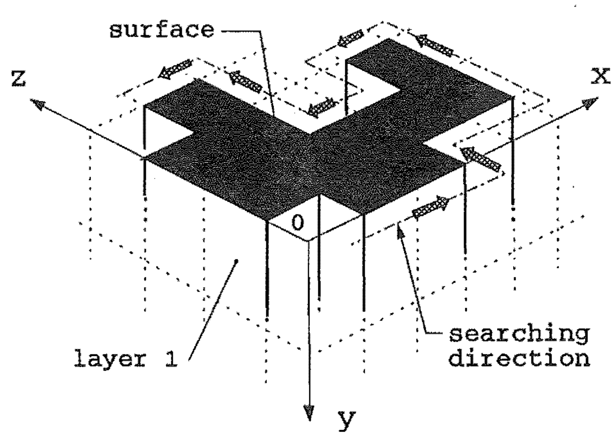


Fig.4.4: Searching pattern.

axes, is used to signify the next searching direction. The searching will stop, for a particular surface, when the coordinates of the current point are the same as those of the first point. Two sets of sub-programs based on the same logic were developed to extract all surface coordinates; the first set is concerned only with the surfaces intersecting the first layer, and the second, with those intersecting the other layers.

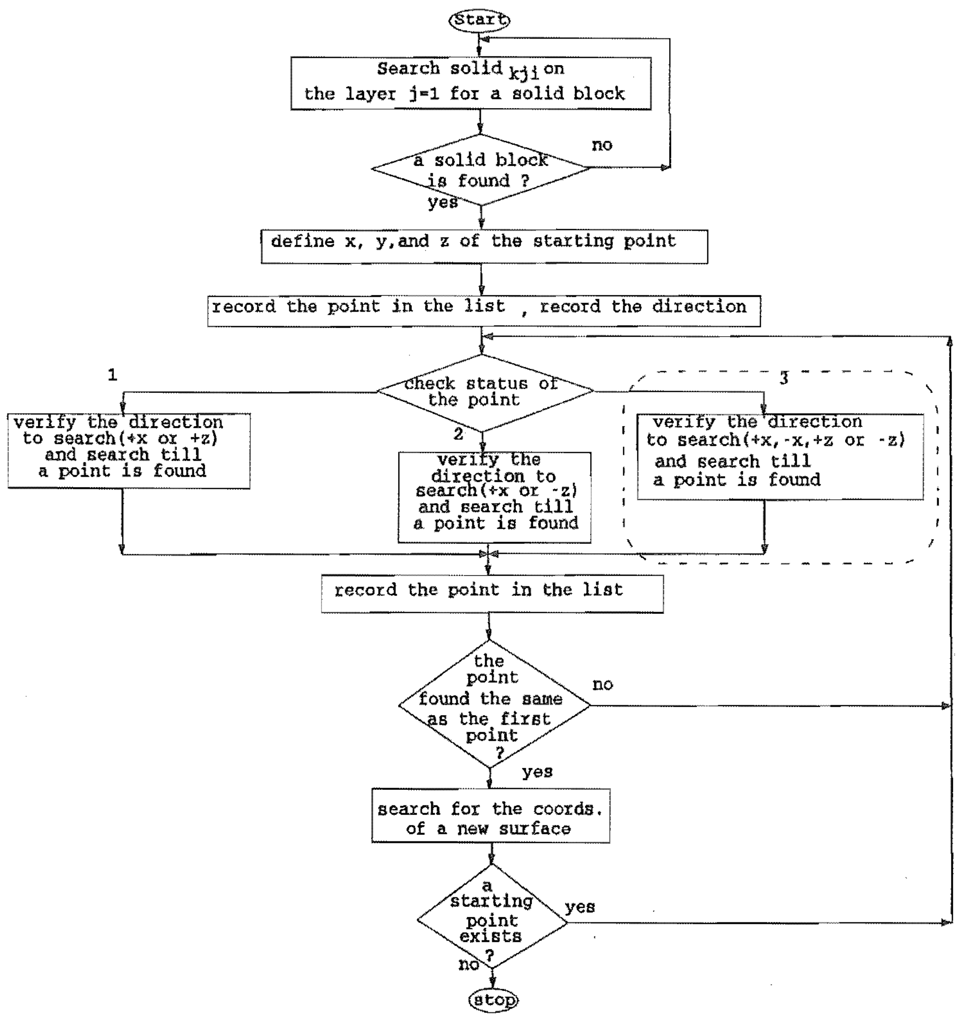
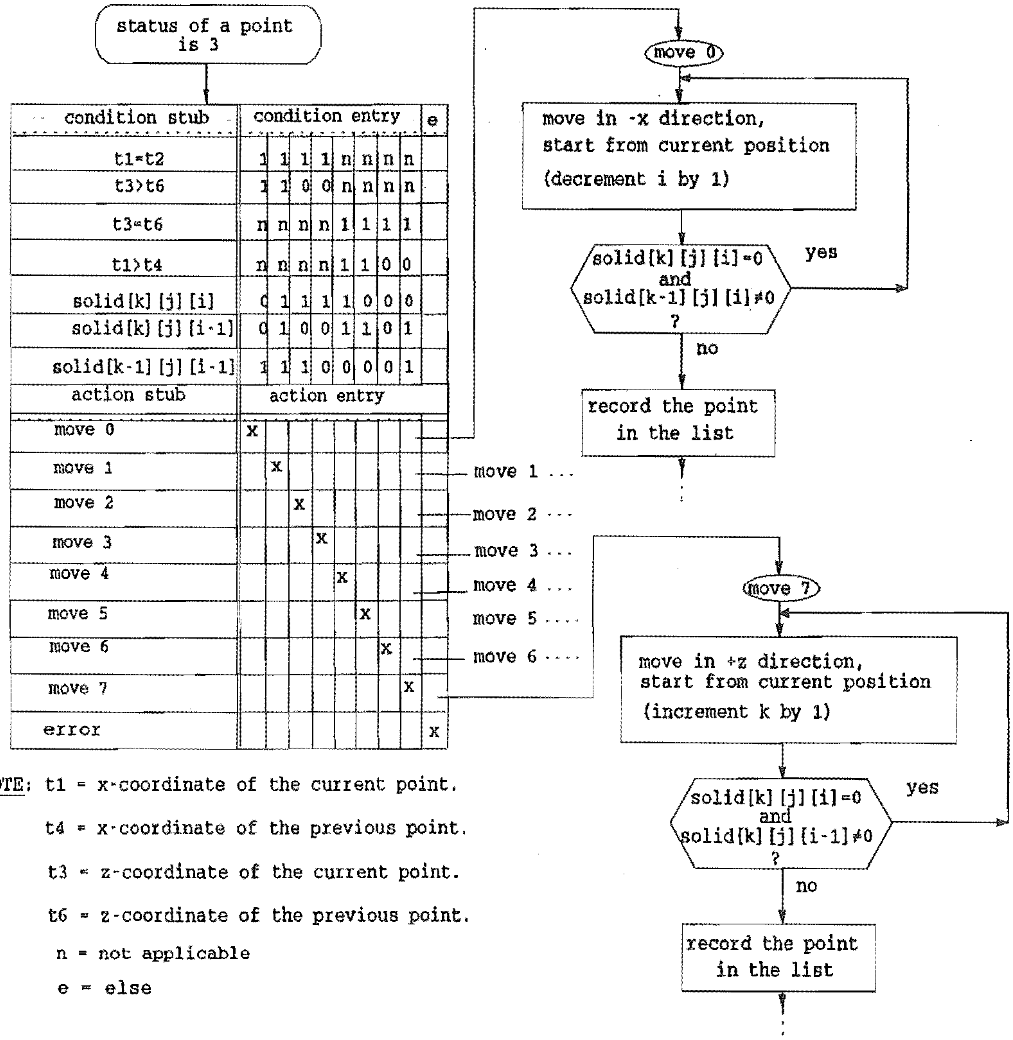


Fig.4.5: The flow chart for the extraction of the surface coordinates.

Fig.4.5 shows the algorithm for extracting the surface coordinates of surface intersections on the first layer. The program searches for a solid block row by row, from row $z=1$ to row $z=7$ in the model. If the first solid block is found, the coordinates of the starting point of the block are determined. These coordinates are then stored in the linked list; at the same time, a number identifying the facing direction is assigned to the surface and stored in the corresponding array. After the first point is found, its position is then used as an index to signify the direction for the next search. This index is defined in the flow chart as the status of a point which is identified by an integer, from 1 to 3. Status 1 signifies that the current point found is on x-axis, and there are only two possible directions: $+x$ and $+z$, to search for the next point. Likewise, status 2, the current point is on z-axis, and the possible searching directions for the next point are $+x$ and $-z$. The decision on which direction to be chosen depends on the conditions of material in the other blocks near the block to which the current point belongs. Unlike the other two, when a point has a status of 3, that point is on neither the x nor the z-axis. In this case, there are 4 possible directions for the next search: $+x$, $-x$, $+z$ and $-z$. Each of these directions depends on the position of the current point relative to that of the previous point as well as the conditions of material around the current point. For example, if a point has a status of 3, and that point has the same x-coordinate as the previous point, but has less in z-coordinate, then the direction for the next search is either $+x$ or $-x$. This last decision depends solely on the material conditions around the current point. To demonstrate this searching procedure further, Fig.4.6 details the portion of the flow chart surrounded by the dotted window. Here, a decision table is used to choose a searching direction.

In the routine for extracting surface coordinates which are on other



condition stub	condition entry								e
t1=t2	1	1	1	1	n	n	n	n	
t3>t6	1	1	0	0	n	n	n	n	
t3=t6	n	n	n	n	1	1	1	1	
t1>t4	n	n	n	n	1	1	0	0	
solid[k][j][i]	0	1	1	1	1	0	0	0	
solid[k][j][i-1]	0	1	0	0	1	1	0	1	
solid[k-1][j][i-1]	1	1	1	0	0	0	0	1	
action stub	**action entry**								
move 0	x								
move 1		x							
move 2			x						
move 3				x					
move 4					x				
move 5						x			
move 6							x		
move 7								x	
error									x

NOTE: t1 = x-coordinate of the current point.
t4 = x-coordinate of the previous point.
t3 = z-coordinate of the current point.
t6 = z-coordinate of the previous point.
n = not applicable
e = else

Fig.4.6: Flowchart and decision table for determining a searching direction.

layers, the decision table has been extensively used to avoid stack over flow as well as to save the coding length. The function (subroutine) for processing the decision table receives the condition entries (in a two-dimensional array) and the conditions of a point (in a one-dimensional array) from the calling program. It then compares the conditions of the point with each set of the condition entries. If a match is found, the searching direction (move 0, move 1...) is passed back to the calling program and a further search is made for the next point. When the current point has the same coordinates as the first point, the search stops; that is a set of coordinates of a surface has completely been extracted.

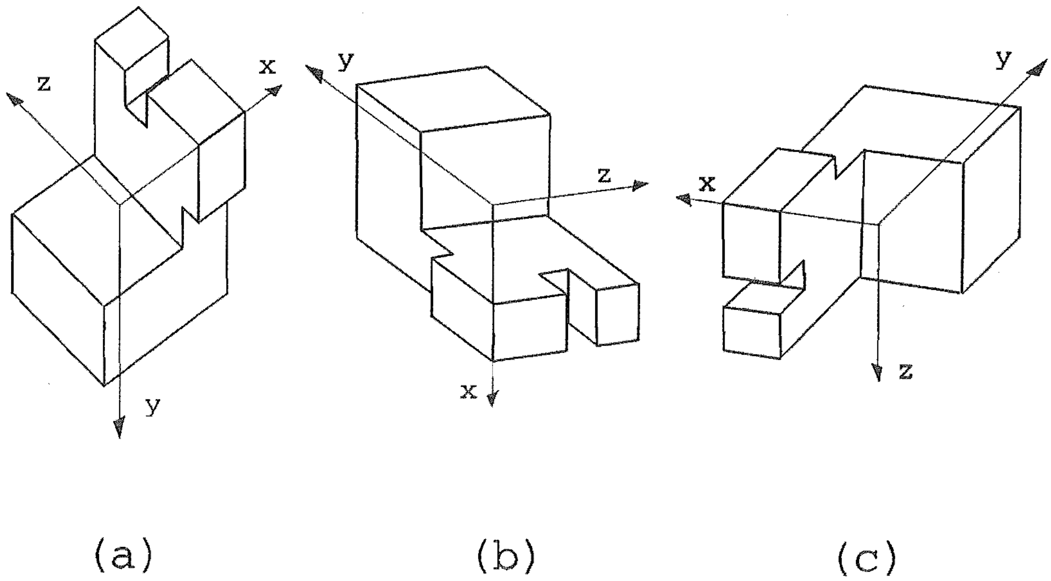


Fig.4.7: Part orientations for surface coordinates extraction.

As mentioned earlier that, in extracting the coordinates of the surfaces perpendicular to y-axis, the extracting routine starts from the top to the bottom layer of the model. To save extra coding, the same routine is used for other surfaces. This is made possible by changing the spatial representation model in such a way that the surfaces which have not had their coordinates been extracted lie in the planes perpendicular to y-axis, and repeating the execution. In other words, the part is rotated for different sets of surface coordinates. Fig.4.6 (a), (b) and (c) show the three orientations of the part for extracting the coordinates of surfaces parallel to xz-, yz- and xy-planes respectively.

4.4 Graphical screen display

After the coordinates of all surfaces have been stored, they are used by the graphics routines in the support module to draw the part on the monitor screen. These graphics routines were written for this particular purpose. The reason for not using the standard graphics routines available in C-compiler is that the analysis is concerned only with features having flat surfaces. These features when shown in an orthogonal projection involve only straight lines. Therefore only few functions are actually required. If a standard graphics package were used, it would require all functions in the package to be loaded into the computer which would occupy a large amount of computer memory.

Fig.4.8 shows the display of the bracket in first angle projection. The numbers in the display are the surface identification numbers. In the front view (top left hand corner), they identify the surfaces on the horizontal planes; in the plan view (below front view) and in side view, they identify those on the vertical planes. The menu window for the user to interact with the computer is shown in the bottom right hand corner of the screen. The user can choose to print the screen on a line printer or ignore the screen and proceed to input other data.

4.5 Production data

The production data are the data that relates to the machining operations; these data include:

(1) the identification of surfaces that make up a machined feature;

(2) the number of stock dimensions, tolerances, and the surfaces

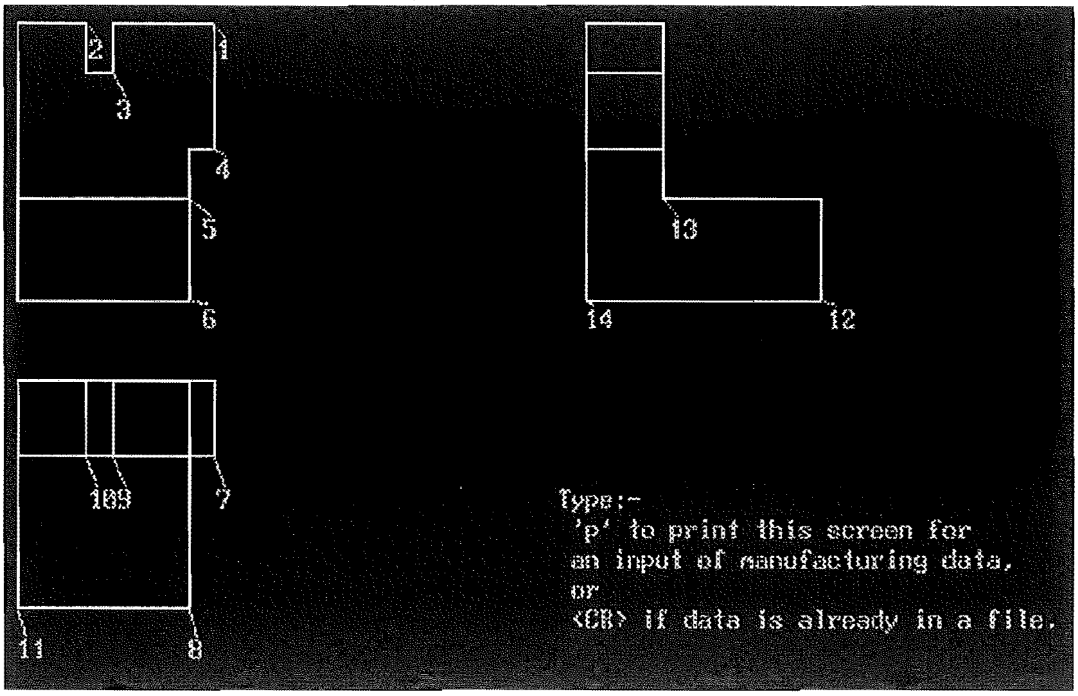


Fig.4.8: Screen display for input.

defined by stock dimensions;

(3) the drawing dimensions and tolerances of the finished part, and the surfaces defined by drawing dimensions;

(4) the number of machining cuts required by each feature;

(5) the depths of cuts; and

(6) the machining (or processing) tolerances for all cuts.

This information is stored in one or two dimensional arrays. The names, types and sizes of these arrays are given in Table 4.1. At the moment, CAPPFD can handle up to 10 features of the same type, and each contains a

Table 4.1: Storage for production data.

Name	Type	Size	Description
facing[i][j]	int	10x5	surface numbers for a facing $operation_{[i]}$
stepc[i][j]	int	10x5	surface numbers for a stepping $operation_{[i]}$
sloting[i][j]	int	10x5	surface numbers for a slotting $operation_{[i]}$
stcfr[] and stcto	char	dynamic	surfaces at the two ends of stock dimensions
stctol[]	float	"	tolerances on stock dimensions
dwgfrom[] and dwgto[]	char	"	surfaces at the two end of drawing dimensions
dwgdim[] and dwgtol[]	float	"	drawing dimensions and tolerances
ncutfc[i]	int	10	number of cuts for facing $operation_{[i]}$
fcdepth[i][j] and fctol[i][j]	float	10x5	depth and tolerance for $cut_{[j]}$ of $facing_{[i]}$
stform[i]	int	10	1 if a stepping operation is made on a formed step; 0 otherwise
ncutst[i]	int	10	number of cuts for step cutting $operation_{[i]}$
stdepth[i][j], stside[i][j] and sttol[i][j]	float	10x5	bottom and side depths of cuts, and tolerance on $cut_{[j]}$ of step $cutting_{[i]}$
slfopen[i][j]	int	10x5	surfaces to which a $slot_{[i]}$ is open
slform[i]	int	10	(same as for step cutting)
ncutsl[i]	int	10	(same as for step cutting)
sldepth[i][j], slside[i][j] and sltol[i][j]	float	10x5	(same as for step cutting)

maximum of 5 surfaces. This allows a combined feature such as a slot on a side of a step to be included in the system. Although the number of cuts for a pre-formed stock (such as a casting, or a forging) is normally less than 3, CAPPFD allows up to 5 cuts to produce a feature.

The depths of cuts for the step and slot cutting operations are input as the bottom depths and side depths. In slot cutting, the difference between these two is obvious -- the bottom depth of cut is the thickness of metal removed to form the bottom of a slot, and the side depth of cut is the thickness of metal removed to form the side of a slot. In step cutting, however, the bottom depth of cut is defined as the thickness of metal removed to form the longer side of a step, and the side depth is the thickness of metal removed on the other side of the step. Although it is realised that the processing tolerance, which is the tolerance on the dimension of each cut, depends on many factors such as the length dimension, the cutting depths, the machining conditions, the condition of the machine-tool, and the operator's skill, the tolerances of both depths are assumed to have approximately the same value. This requires the user to use an appropriate mean value of tolerance for both bottom cut and side cut.

The arrays which store the slot opening surfaces (slfopn[][]) are required for the modification of the spatial representation model for various shapes of the machined part. For example, if a slot is cut in a solid stock, the slot has to be removed from the model so that it represents the condition of the workpiece prior to the cut being made, that is the slot surfaces will be required to merge. The array slfopen[][] serves this function. More details of the procedure for changing the spatial representation model will be discussed in chapter 6.

The arrays stform[] and slform[] store the flags to signify if a step or a slot is machined from a formed feature. This information is required for the modification of the workpiece model, and for the input of the production data. In the latter, if the flag is on, the bottom and the side cutting depths together with the machining tolerance must be entered for the first cut; otherwise, only the tolerance is required. Note that the tolerances of the stock and not the dimensions are required by the system. CAPPFD will show these dimensions in the tolerance charts. But, if stock dimensions are available, the user must work out the number of cuts and the cutting depths from the stock dimensions and the finished part dimensions. In this case, the results in the tolerance charts must agree with the stock dimensions.

4.6 Data input

```
Enter file name for storing data: work.d

Number of stock dimensions
(type 0 if no stock dimension): 3
Enter stock dimensions:-
# 1:- stk. dim. from: 1
      stk. dim. to   : 6
      tolerance(mm): 0.15
# 2:- stk. dim. from: 7
      stk. dim. to   : 11
      tolerance(mm): 0.15
# 3:- stk. dim. from: 12
      stk. dim. to   : 14
      tolerance(mm): 0.15

Number of drawing dimensions: 10
Enter drawing dimensions:-
# 1:- dwg. dim. from: 7
      dwg. dim. to   : 9
      dimension(mm): 39.00
      tolerance(mm): 0.10
# 2:- dwg. dim. from: 9
      dwg. dim. to   : 10
      dimension(mm): 10.00
      tolerance(mm): 0.09
```

(a)

```
Enter the number of facing operations
      (type 0 if no facing operation): 6
facing #1:- (type 0 to stop)
 on surface: 12
 on surface: 0
  number of cuts: 2
   cut # 1: depth of cut (mm): 5.00
            mc tolerance (mm): 0.10
   cut # 2: depth of cut (mm): 1.00
            mc tolerance (mm): 0.05
facing #2:- (type 0 to stop)
 on surface: 6
 on surface: 0
  number of cuts: 2
   cut # 1: depth of cut (mm): 5.00
            mc tolerance (mm): 0.10
   cut # 2: depth of cut (mm): 1.5
            mc tolerance (mm): 0.08
facing #3:- (type 0 to stop)
 on surface: 1
 on surface: 2
 on surface: 0
  number of cuts: 1
   cut # 1: depth of cut (mm): 6.00
            mc tolerance (mm): 0.16
```

(b)

Fig.4.9: Dialogue for data input.

As mentioned before CAPPFD reads the spatial representation model of the part from a data file, and interacts with the user for the production data. Fig.4.9, shows examples of the dialogue for the input of: (a) stock and drawing data, and (b) facing data. The data from this interaction are stored in a data file under a name given by the user. During the dialogue, if there are any mistakes in entering the data, the user cannot make the corrections; but the corrections can be made afterwards in the editing session. The editing routine provides three main types of editing: adding, deleting, and modifying. After an editing session, the edited data are re-stored in the data file.

An example of editing session is shown in Fig.4.10 (a) to (f), which illustrate the steps in modifying the bottom and side depths of the machining cut # 2 of the step cutting operation # 2. The underlines are input by the user. At any stage, the user can terminate a particular editing session and go back to the previous menu by typing 0.

```
Do you want to edit the data (Y or N) ?
Select an item to edit (type a number) :-
(1) Stock data
(2) Drawing data
(3) Cutting data
(4) Quit
```

(a)

```
Editing of cutting conditions:-
Select a number:
  (1) Facing data
  (2) Step cutting data
  (3) Sloting data
  (4) Quit
------------------------------------------
```

(b)

```
Editing step cutting data session:-
Select a number:
  (1) Add new step cutting data
  (2) Delete step cutting data
  (3) Modify existing data
  (4) Quit
------------------------------------------
```

(c)

```
Modifying step data (0 to end):-
--------------------
steping no.    faces
   1           1 3 5
   2           8 10
   3           2 15
--------------------
steping no.? 2
Is the cut made on solid stock(Y or N)?
```

(d)

```
Modifying step data (0 to end):-
Step faces: 8 10   : step is cut on solid stock
------------------------------------------------
cut no.     depth      side       tolerance
  1         0.000      0.000        0.1500
  2         1.000      1.500        0.0080
------------------------------------------------
cut no.? 2
  bottom depth of cut (mm): 1.5
  side   depth of cut (mm): 1.0
         mc tolerance (mm): .008
```

(e)

```
Modifying step data (0 to end):-
Step faces: 8 10   : step is cut on solid stock
------------------------------------------------
cut no.     depth      side       tolerance
  1         0.000      0.000        0.1500
  2         1.500      1.000        0.0080
------------------------------------------------
cut no.? 0
```

(f)

Fig.4.10: Data editing.

4.7 Data output

The outputs from CAPPFD are:

(1) the sequence of machining operations,

(2) the locating surfaces on the workpiece for each operation, and

(3) the tolerance charts.

To save the computer memory, the outputs from the sequencing module are stored in the same arrays of features (facing[][], stepc[][], and sloting[][]) as the inputs. The only difference is the order in each array. In other words, the positions of the row elements in each feature array are changed by the sequencing module.

Table 4.2: Arrays for storing 3-2-1 location systems.

Name	Type	Size	Description
loffc3[i][j], loffc2[i][j], loffc1[i][j]	int	10x5	3-, 2- and 1-point locating faces for facing $\text{operation}_{[i]}$.
locfc3[i][j][k], locfc2[i][j][k], locfc1[i][j]	float	10x3x3 10x2x3 10x3	coordinates for placing 3-, 2- and 1-point locating symbols.
lofst3[i][j], lofst2[i][j], lofst1[i][j]	int	10x5	locating surfaces for step $\text{cutting}_{[i]}$.
locst3[i][j][k], locst2[i][j][k], locst1[i][j]	float	10x3x3 10x2x3 10x3	coordinates for locating symbols.
lofsl3[i][j], lofsl[i][j], lofsl[i][j]	int	10x5	locating faces for $\text{slotting}_{[i]}$.
locsl3[i][j][k], locsl2[i][j][k], locsl[i][j]	float	10x3x3 10x2x3 10x3	coordinates for placing locating symbols.

For the locating surfaces, the data are stored in three arrays of floating point numbers as shown in Table 4.2. Also shown in the table are the three arrays for storing the coordinates of the location systems. These coordinates are used only for positioning the locating symbols on the part while it is displayed on the screen. They are not intended to be actual positions because the tool designer, after deciding the types and sizes of the locators, chooses the appropriate positions on an identified surface to suit the locators.

In locating the part, CAPPFD proceeds from the finished part to the raw stock. After a location system for an operation has been successfully found the data are stored, and the part together with the location system are then displayed on the screen (or printed out on a printer). CAPPFD does not provide the storage for these screen outputs; therefore, each display will appear on the screen only once, and after that the user cannot recall the display.

Table 4.3: Data for tolerance charting.

Name	Type	Size	Description
mdf[] and mdt[]	char	dynamic	surfaces, identified by letters, at the two end of stock dimensions.
stol[]	float	"	tolerances on stock dimensions.
dwf[] and dwt[]	char	"	surfaces, identified by letters, at the two ends of drawing dimensions.
dbas[] and dtol[]	float	"	basic dimensions and tolerances of the finished part.
loc[] and cut[]	char	"	locating surfaces and cutting surfaces.
sterv[]	float	"	stock removal.
wtol[]	float	"	machining tolerances.

Table 4.3 shows the data for the tolerance chart module. They are included here because they are the outputs from the previous executions, and have been transferred into the appropriate forms for the charting module.

The tolerance charts are drawn for the three principal orthogonal views of the part. Again, there is no storage for the screen display of the charts; that is, after one chart has been displayed, all the variables involved in the calculations and in the drawing of the chart are initialized to the next set of data, and the execution is then repeated.

4.8 Conclusion

CAPPFD may receive data in two ways, by directly reading a data file, or by interacting with the user. All of the production data are stored in arrays of one or two dimensions, and they are arranged in 'pairs'. That is, the data relevant to the same feature or operation are identified by the same index number. This concept makes the data structures simple and helps simplify the tolerance chart algorithm. The user has to prepare the production data from the stock and drawing dimensions manually before entering them into the system. Also the user is responsible for deciding the appropriate values of the processing tolerances. The outputs from CAPPFD are shown on the screen. To record the outputs, CAPPFD prints them on the line printer.

5. MACHINING SEQUENCE PLANNING

Most of the CAPP systems, for prismatic parts, developed so far lack a capability to generate the machining sequence; they are used mainly for selecting cutting conditions, cutting tools, and machine-tools. Some do incorporate such capability, but it is limited to only a certain kind of feature, eg., a counter-bored hole, or an internal thread. There have been no reports of attempts to sequence the machining operations based on the dimensional relationship among features. It is in this respect that CAPPFD differs from other systems. It is capable of generating the machining sequence automatically; that is without any intervention from the user. This chapter explains the development of the sequencing algorithm adopted in CAPPFD.

5.1 Forward and backward planning

In computerized process planning, there are two basic strategies for sequence planning: forward planning and backward planning. Forward planning starts the sequence from a raw or stock shape and ends up with a finished product shape. In this case, the number of surfaces on the workpiece increases as more machining operations are performed. Backward planning, on the other hand, works in the opposite direction; it starts from a finished part and progresses towards a stock part, or from more surfaces to less surfaces. Thus, in backward planning, the machining sequence required is the reverse of that considered in the planning process. Backward planning, however, offers advantages over forward planning, such as simplicity in manipulating of the geometrical part model representation, less data storage required, and economy in execution [37].

The weak points of the existing systems that use both strategies are: they are concerned only with the changes in the geometrical shape of the workpiece, and no consideration being given to the dimensional control, which is the most essential part of process planning.

CAPPFD utilizes the advantages of backward planning by incorporating the concept in the routines for locating the workpiece, but it is not used for sequencing the operations.

5.2 Basic sequencing concept

Because the sequence of machining operations in quantity production is based on where to locate the workpiece for machining, the feature that is likely to be machined first is the one that has more potential to be used as a locating feature for machining other features.

Normally, in machining, flat surfaces are machined before steps and slots. This is because they can provide locating surfaces for other operations. The face of a step can sometimes be used as a locating surface. However, it is very rare that a workpiece is located from a surface of a slot. For these reasons the general sequencing plan is that all flat surfaces are machined before the steps; the steps are machined before the slots. There still remains the sequence for machining the features of the same type. This sequence depends on the following main factors:

(1) the number of dimensions on a feature relating to a certain type of feature,

(2) the closeness of tolerances on dimensions relating to a certain type of feature, and

(3) the degree of geometric control that a feature can offer, if it is

chosen to be a locating feature.

For example, in the case of flat surfaces, if a flat surface has more dimensions relating to other flat surfaces, that surface is to be machined before the others; but, if a tie exists, the closeness of tolerances on dimensions will be considered; then, if a tie still exists, the number of dimensions relating to the steps will be considered. If all dimensional relationships are equal, the priority will be given to the surface capable of giving the highest degree of geometric control.

This concept is, therefore, based on the practicality of machining a type of feature, and on dimensional and geometric control. In the following sections, the detailed implementation of the concept is explained.

5.3 Ranking of machining operations

As discussed in chapter 4, three two-dimensional arrays, namely, facing[][], stepc[][] and sloting[][], are used to store the surface numbers for facing, step cutting and slotting operations respectively. These arrays can be referred to as feature arrays or operation arrays, because each of them contains the surfaces of the same feature type, and requires the same type of operation.

To sequence the operations in a particular feature array, the row elements of the corresponding array are swapped according to the criteria outlined above, and when a swap is made all information pertaining to the swapped features is also exchanged.

There are 2 steps in deriving the sequence for the operations of the same type, ie, ranking and modifications. In this section, the focus is on the first step.

Table 5.1: Data for operations sequencing.

Name	Type	Size	Description
mcf[]	int	dynamic	surfaces requiring machining.
unmac[][]	int	dynamic	unmachined surfaces.
relfc[i][]	int	10x10	surfaces dimensionally relating to $face_{[i]}$.
relst[i][]	int	10x10	surfaces dimensionally relating to $step_{[i]}$.
relsl[i][]	int	10x10	surfaces dimensionally relating to $slot_{[i]}$.
scfc[i]	int	10	number of dimensions relating to $face_{[i]}$.
scst[i]	int	10	number of dimensions relating to $step_{[i]}$.
scsl[i]	int	10	number of dimensions relating to $slot_{[i]}$.
rankfc[i]	int	10	ranking number of $face_{[i]}$.
rankst[i]	int	10	ranking number of $step_{[i]}$.
ranksl[i]	int	10	ranking number of $slot_{[i]}$.

In ranking, some intermediate data, which have been derived from the data input, are required. These data are stored in the variables listed in Table 5.1. The ranking procedure starts by counting the number of dimensions relating to a feature, and assigns that number to the corresponding score arrays (scfc[], scst[] or scsl[]). Then, the elements of the score array are sorted in a descending order. During sorting, any swap of the elements in the score array will cause the related data to swap accordingly. After this, each operation is given, based on its score array, a ranking number: the higher the rank the earlier the feature is to be machined. The ranking numbers are stored in three one-dimensional arrays (rankfc[], rankst[] and ranksl[]) corresponding to the three feature types. The maximum possible integer value to be assigned to the elements of each ranking array depends on the number of operations of the same type. For example, if there are five facing operations, the maximum ranking value will also be five. When a tie exists, all the elements in the ranking array corresponding to the tied operations are assigned the same number. For example, if $scfc_{[i]}$ = { 2, 2, 1, 1, 0 }, where i=1,2...5, then $rankfc_{[i]}$ = { 5, 5, 3, 3, 1 }. Note that $scfc_{[5]}$ = 0 does not mean this surface has no dimensional relationship with the other features, but it means the this feature is dimensionally referenced by features that do not require machining. Fig.5.1 shows a simplified flowchart for ranking facing operations. The same logic is used for ranking other operations. Also note that the relationship arrays (relfc[][], relst[][] and relsl[][]) store the surface numbers of the surfaces that are dimensionally referred to by a feature. These surfaces are either those requiring or not requiring machining.

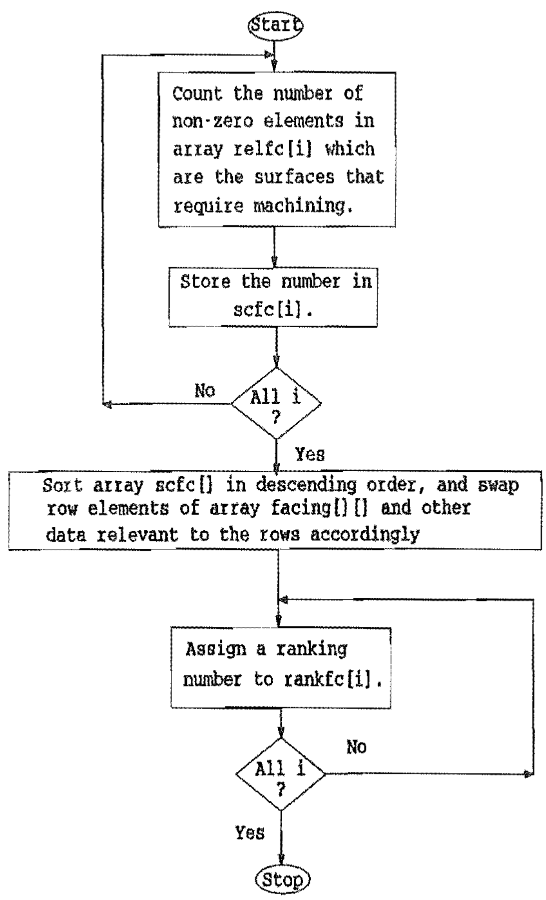


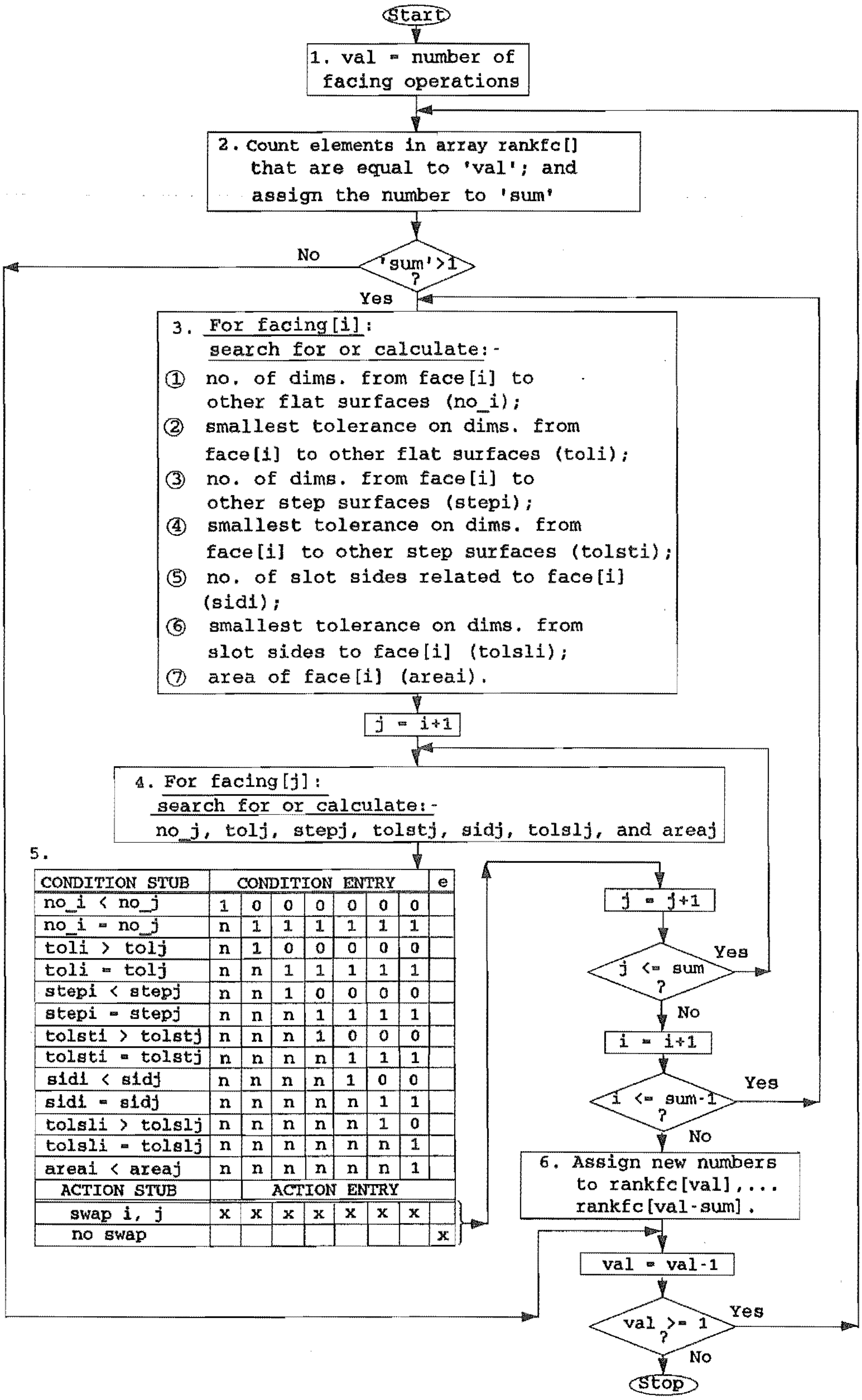
Fig.5.1: Flowchart for ranking facing operations.

5.4 Sequence modifications

After ranking, some operations may have the same ranking number. That is to say, from the baseline demensioning point of view, they are equally qualified for being machined at the same time, which is not possible in the case in conventional milling operations. Therefore, further modification of the sequence is required for those operations having the same ranking number.

Since a slot is not used for locating the workpiece, the rules for modifying the sequence of slotting operations are different from those for facing and step cutting.

The flowchart in Fig.5.2 shows the procedure for modifying facing operations. It starts by first assigning the number of facing operations to an integer variable, 'val' (box 1); 'val' must start from this value because it is the maximum ranking number. Then, the elements in array rankfc[] which are equal to 'val' are counted, and the result is assigned to a variable 'sum' (box 2). If 'sum' is more than 1, it means there are more than one elements in array rankfc[] that is equal to 'val', so the operations corresponding to these elements require reshuffling. In box 3, the variables, which are the factors for this reshuffling, pertaining to $face_{[i]}$ are searched or calculated. Box 4 shows similar variables for $face_{[j]}$. Based on these factors, the decision table in box 5 decides if a pair of operations needs swapping. It should be noted here that the first 6 factors in box 3 are concerned with dimensional control; the last, with geometric control, and that the conditions in the decision table are evaluated sequentially. This means if two features can equally provide the same degree of dimensional control, their sequence is then based on the geometric control criterion -- the area bounded by the



CONDITION STUB	CONDITION ENTRY							e
no_i < no_j	1	0	0	0	0	0	0	
no_i = no_j	n	1	1	1	1	1	1	
toli > tolj	n	1	0	0	0	0	0	
toli = tolj	n	n	1	1	1	1	1	
stepi < stepj	n	n	1	0	0	0	0	
stepi = stepj	n	n	n	1	1	1	1	
tolsti > tolstj	n	n	n	1	0	0	0	
tolsti = tolstj	n	n	n	n	1	1	1	
sidi < sidj	n	n	n	n	1	0	0	
sidi = sidj	n	n	n	n	n	1	1	
tolsli > tolslj	n	n	n	n	n	1	0	
tolsli = tolslj	n	n	n	n	n	n	1	
areai < areaj	n	n	n	n	n	n	1	
ACTION STUB	ACTION ENTRY							
swap i, j	x	x	x	x	x	x	x	
no swap								x

Fig.5.2: Flowchart for modifying facing sequence.

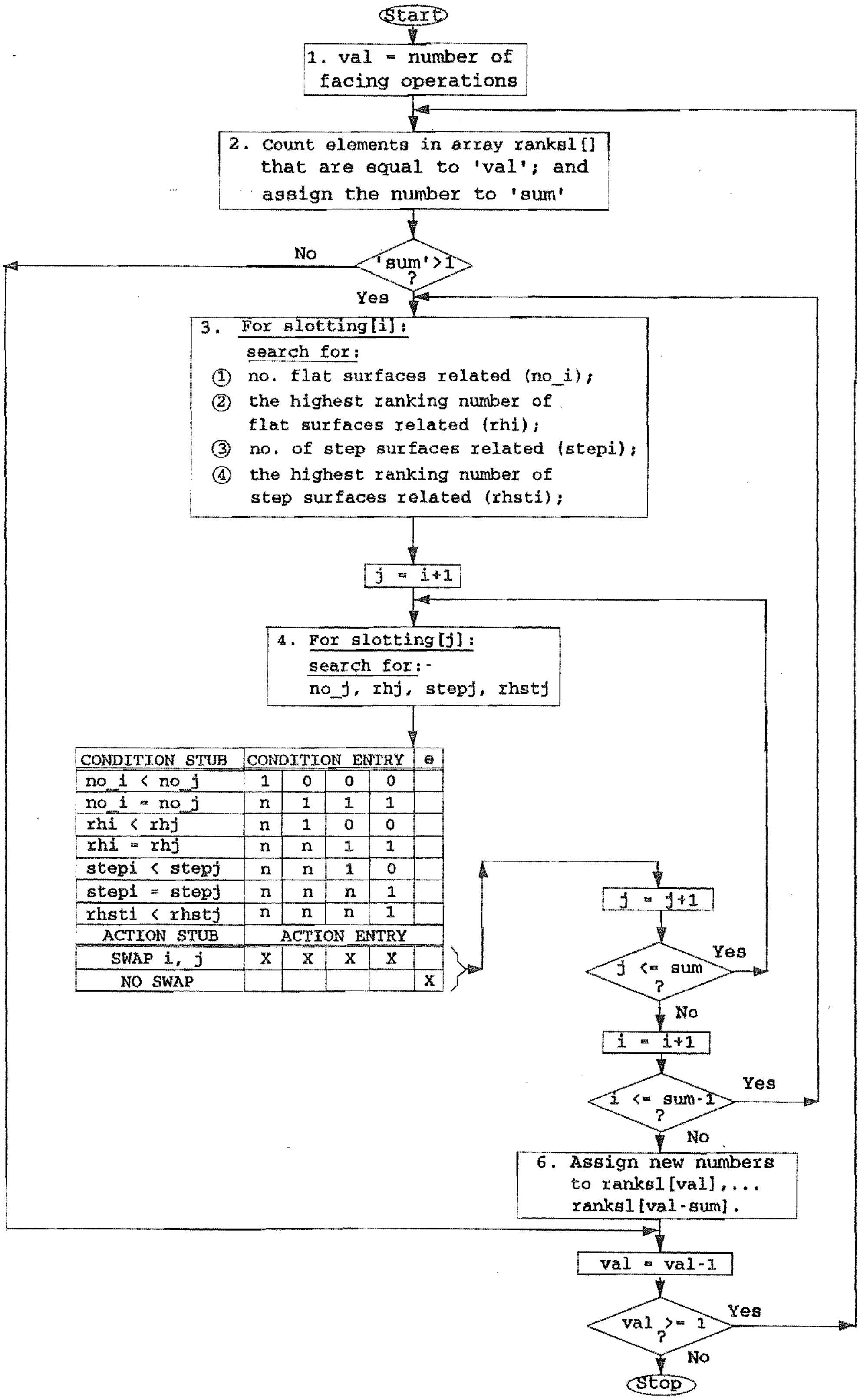
surface with three point-locators. When all 'sum' operations have been reshuffled, new ranking values are assigned to those operations (box 6) so that they do not have the same ranking value.

The flowchart for modifying sequence of step cutting operations is similar to Fig.5.2 except that all data pertain to the steps; it is not shown here.

However, the procedure for modifying the slotting sequence needs some explanation. Though the logic is, in general, the same as for the facing and step cutting operations; since a slot is not used for locating the part, the criteria for evaluating the sequence are based only on the dimensional control of the part. Fig.5.3 shows the flowchart, and the criteria are listed in box 3. The general idea behind these criteria is that a slot which has a relationship of higher importance in dimensional control should be given a higher priority, being machined before the others, so that it can provide a more accurate gauging reference in the inspection of other slots. The factors are listed according to the order of importance of the factors; the more important ones come first. The rules in the decision table in box 5 are executed sequentially as in the case of facing.

5.5 Adjustments for combined slots

A combined slot is a slot which contains one or more other slots. Slots 3 and 5 in Fig.5.4 are examples of the combined slot; slots 3 has slot 0 at its bottom face, and slot 5 contains another two slots. In practice, the slots closer to the top surface are normally machined before the lower ones. The reasons for this are: it is faster to machine because larger cutter can be used for the slots on the top, and a more uniform cutting action can be maintained.



CONDITION STUB	CONDITION ENTRY				e
no_i < no_j	1	0	0	0	
no_i = no_j	n	1	1	1	
rhi < rhj	n	1	0	0	
rhi = rhj	n	n	1	1	
stepi < stepj	n	n	1	0	
stepi = stepj	n	n	n	1	
rhsti < rhstj	n	n	n	1	
ACTION STUB	ACTION ENTRY				
SWAP i, j	X	X	X	X	
NO SWAP					X

Fig.5.3: Flowchart for modifying slotting sequence.

As the sequencing module treats a combined slot as two or more individual slots, the sequence obtained may have a lower slot machined before the upper one. This requires some adjustments so that the sequence will comply with practice.

A subprogram was written to adjust the slotting sequence. It makes use of the surfaces to which a slot is open (slfopen[][]) to indicate if the slot is a lower slot. slot. If so, that slot is cut after the upper one. Then, the row elements in slotting array corresponding to the upper slot are shifted to be in front of those corresponding to the lower slot. For instance, supposing the slotting sequence in Fig.5.4 is { 0, 1, 2, 3, 4, 5 }. That is, slot # 0 is machined before slot # 1, slot # 1 before slot # 2, etc. The slot numbers are surrounded by a circle in the figure. After the adjustment, the sequence will become { 3, 0, 1, 5, 2, 4 }. Fig.5.5 is the flowchart showing the logic for adjusting the slotting sequence.

Whenever there is a swap of operations in the sequence either in the ranking, the modifying, or the adjusting phrase, all other relevant data are also swapped.

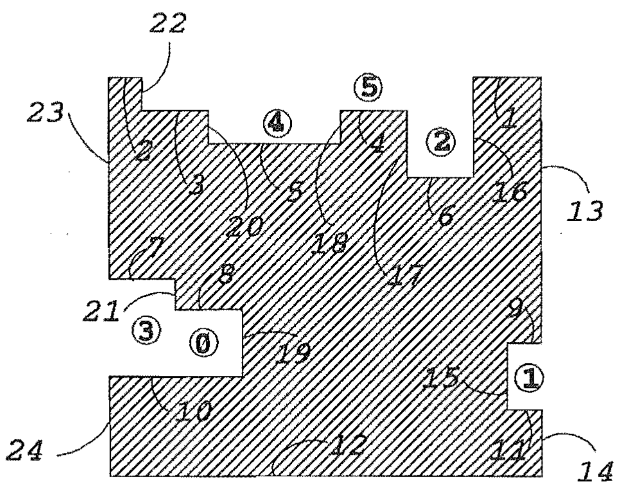


Fig.5.4 Combined slots.

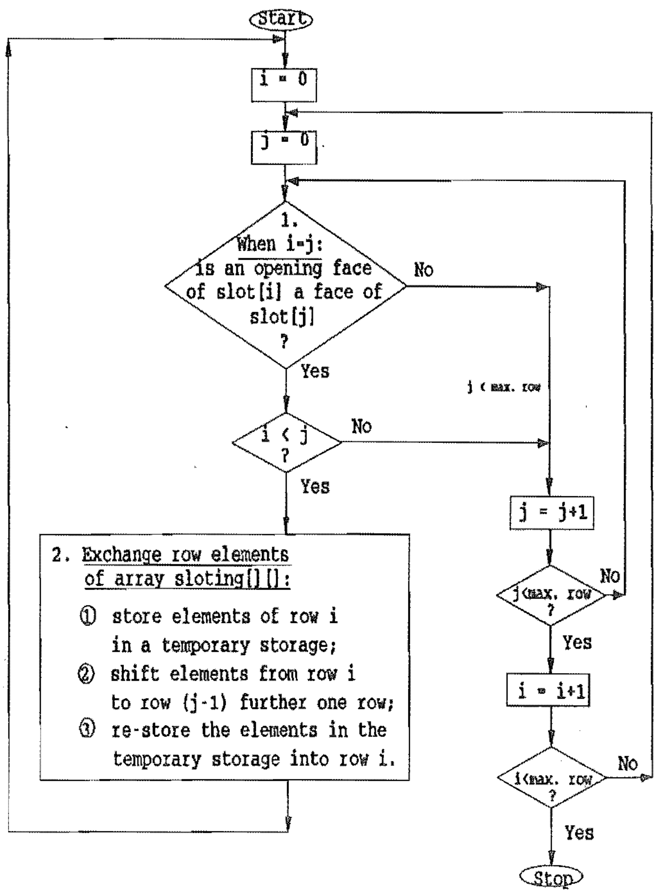


Fig.5.5: Flowchart for adjusting slotting sequence.

5.6 Calculation of surface locating area

CAPPFD uses the triangular locating area (the area surrounded by three point-locating pins) as the means for measuring the degree of geometric control; the larger the area is, the better geometric control it can offer. The area may cover more than one surface on the same level, and it may be a machined or an unmachined surface. Examples of these surfaces are shown in Fig.5.6.

To calculate a triangular locating area, for instance, on surfaces d and e in Fig.5.6, first, the coordinates of the extreme edges: 1-2, 2-3, 4-5, 5-6 and

7-8, of the surfaces are stored temporarily in three one-dimensional arrays (x-, y- and z-coordinates are stored separately). Then, these arrays are used to calculate the triangular areas formed by the coordinates of three points. And, finally, the largest area is chosen to be the surface locating area. The same procedure is also applied to calculating of the locating surface on a side of a step.

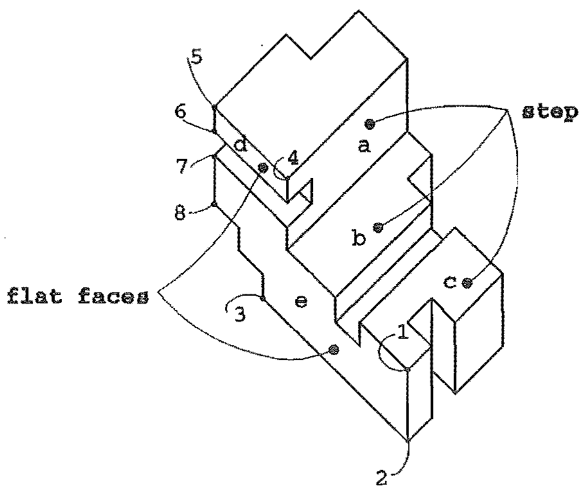


Fig.5.6: Examples of locating areas.

5.7 Conclusion

All facing operations are carried before step cutting operations, and the step cutting operations are performed before slotting operations. The sequence of the operations of the same type is based on the baselines for dimensioning, closeness of tolerances, the relationships to other types of features, and the triangular locating areas. Dimensional control over the workpiece is the primary objective of the sequencing routines.

6. LOCATION SYSTEMS

The location system adopted in CAPPFD is the well-known 3-2-1 location system, which is accomplished by placing 3 locators on the largest surface, 2 locators on the second largest, and 1 locator on a surface perpendicular to the first two. This is a theoretical location system which is a result of the workpiece control analysis. The tool designer is responsible for transforming it to a physical system that satisfies the theoretical requirements. It can also act as an input to an automatic fixture design system such as that described by Ngoi [52].

CAPPFD produces the location system for machining each feature in a form of 'process pictures' which can be used as a basis for the tool designer to identify the appropriate locating surfaces. In this chapter, the algorithm for locating the workpiece is discussed.

6.1 Process picture

A process picture is a piece of information concerning how a workpiece is to be located, supported, and clamped for machining. It is a means for transmitting the ideas from the process planner to the tool designer. It describes the workpiece as it appears just after an operation has been completed. Normally, a process picture contains information such as the drawings of the workpiece, the processing dimensions, the feature to be machined, and the symbols indicating the locating, supporting, and clamping points.

However, in CAPPFD, a simplified process picture, as shown in Fig.6.1, is used. The surfaces are identified by numbers. All processing dimensions are omitted because the outputs from the package include a set of tolerance charts which show all of these dimensions. The locating surfaces are indicated by triangular symbols.

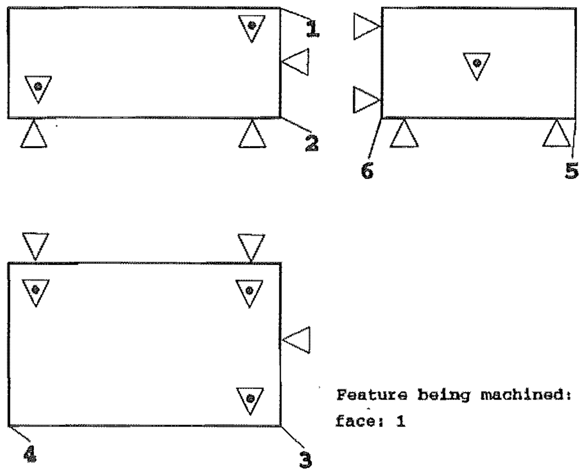


Fig.6.1: A process picture.

6.2 Backward planning: the application

As mentioned in chapter 5 CAPPFD makes use of backward planning in locating the workpiece. The first operation for which the locating module searches for the location system is the last operation in the sequence, ie, one of the slotting operations. At this stage, all surfaces on the part, except those belonging to the slot being machined, are candidates for being locating surfaces. After the part has been successfully located, the model is modified so that it represents the geometry of the part just before the slot was machined. The modifications are also made on the surfaces numbers in various arrays that store them. (This will be discussed later in this chapter.) CAPPFD, then, extracts the coordinates of the surfaces of the new model and store them in the same variables that have been used before. Then, the locating procedure continues for the second last operation. This process is repeated until all location systems for all operations have been found; that is the process ends when the workpiece becomes a stock part.

6.3 Type of locating surface

On a machined part presented for locating, there are two types of surfaces; machined and unmachined surfaces. The machined surfaces are those having been machined previously, in the earlier operations. The unmachined surfaces are either surfaces that require machining but are not yet machined or those do not require any machining.

In backward planning of the location systems, the number of unmachined surfaces increases as the planning goes on, because some of the machined surfaces change to unmachined surfaces. To demonstrate this, consider the following: having completed locating the workpiece for a facing operation, the locating module identifies all the surface numbers just machined as the unmachined surfaces, and adds them to the unmachined feature array (unmac[][]). In the case of a step, it depends on whether the step cutting is cut on a pre-formed step or from solid stock. If it is cut on a pre-formed step, the step surface numbers will be transformed to the unmachined feature array. But, if it is cut on solid stock and the surface of the solid stock at that particular region does not requires further machining, no transformation is made. After this, the transformed surface numbers will also be eliminated from the array storing the machined surfaces (mcf[]).

CAPPFD gives a higher priority to the machined surfaces in locating the workpiece.

6.4 Slot base and step base

The concept of 'slot base' and 'step base' is introduced into the CAPPFD system to decide the position of the cutting tool relative to a slot or a step being cut. This concept is essential for the input of depths of cut for machining both features, as well as for locating the workpiece -- in the case of a slotting operation.

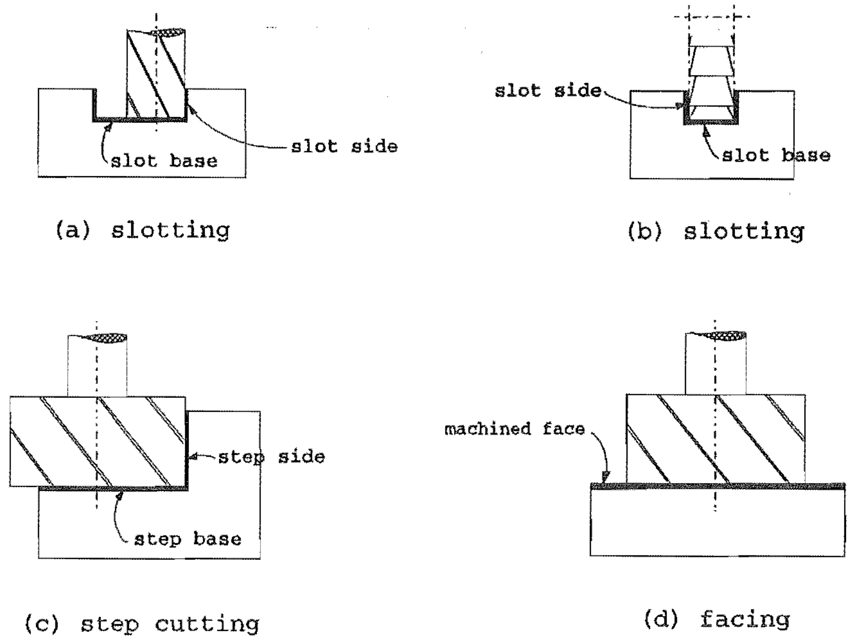


Fig.6.2: Slotting, step cutting and facing operations.

The slot base is defined as the bottom surface of a slot. While it is being machined, this surface is always facing to the milling cutter, either an end mill or a side and face mill, as shown in Fig.6.2. It follows that the surface which is parallel to the slot base and is on the same side as the cutting tool will never be used as a locating surface for cutting the slot.

Although the concept of step base is concerned only with types of cutting relating to depths of cuts for a step, which is part of the input data, it is found appropriate to discussed it here, for it relates to the relative position of the cutting tool. Normally, in machining a step, the operator tries to minimise the distance the tool moves while cutting by feeding the tool in a direction parallel to the shorter side of the step, so that the step can be cut faster. In Fig.6.2(c), the step base would be regarded as the longer side of a step.

Regarding the locating surfaces for machining a step, no surface on the same side as the cutter can be used as a locating surface.

The following are the a summary of the rules for identifying the locating surfaces:

(1) In facing operation, the surfaces that are parallel to and with normals pointing to the same direction as that of the surface(s) being cut are not used for locating.

(2) In cutting a slot, the surfaces that are parallel to and with normals pointing to the same direction as that of the slot base are not used for locating the workpiece.

(3) In cutting a step, the surfaces that are parallel to and with normals pointing to the same direction as those of the step sides are not used for locating.

In applying the concept to depth of cut, the bottom depth is the amount of metal to be removed to produce the slot or step base, and the side depth is, to produce the side of the slot or step.

6.5 Searching for locating surfaces

Before a search for a location system for an operation can be made, all the qualified locating surfaces, machined and unmachined, are first searched and stored in two one-dimensional arrays of 'structure', larea[] and ularea[], as listed in Table 6.1. The procedure for searching for machined or for

Table 6.1: Temporary storage for locating areas.

Name	Type	Size	Description
larea[]	structure*	dynamic	stores all machined surfaces that may be used for locating the part for an operation
luarea[]	structure*	dynamic	stores all unmachined surfaces that may be used for locating the part for an operation

* NOTE: Structure is another type of variable in C. It consists of several members which can be of different data types, and it is given a name for referencing. The structure 'ainfo' is created for larea[] and luarea[]; it has the following members:

```
struct ainfo {
    float area;
      int face[5];
    float x[3];
    float y[3];
    float z[3];
}
```

unmachined locating surfaces are basically the same. The only difference is the data involved in the procedure.

The flowchart in Fig.6.3 shows the general steps in searching for all possible machined surfaces qualifying for locating a workpiece for machining a slot.

The procedure starts with those surfaces requiring facing operations. If they have been previously machined and are parallel to and not facing the same direction as the slot base, they will be stored in larea[]. Also at this time the triangular locating area is calculated. This area and its coordinate are then stored in larea[], under different member names. When all surfaces from facing operations have been considered, the same process is repeated for the step surfaces.

The arrays larea[] and luarea[] are both temporary storage in the sense that once a location system has been found from them, their memory locations will be freed, and will be re-allocated again when required.

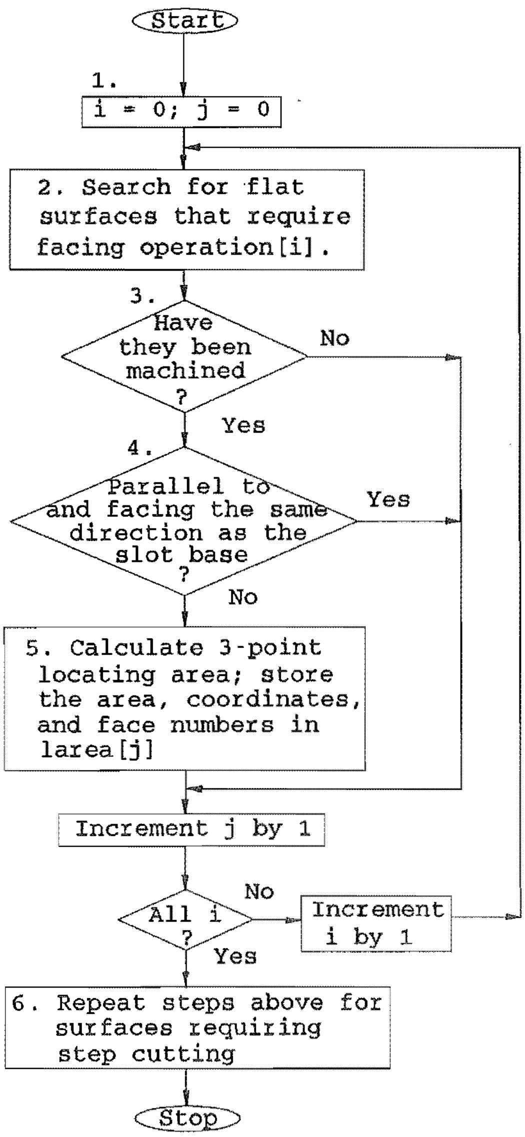


Fig.6.3: Flowchart for searching for the machined surfaces for locating the workpiece in slot cutting.

6.6 Searching for a location system

The first step in the process of searching for a location system is to sort the arrays laera[] and luarea[] in a descending order of the locating areas. The following logic is then applied:

(1) Search the machined locating surfaces; if no appropriate faces are found for a system, the unmachined locating surfaces are then searched.

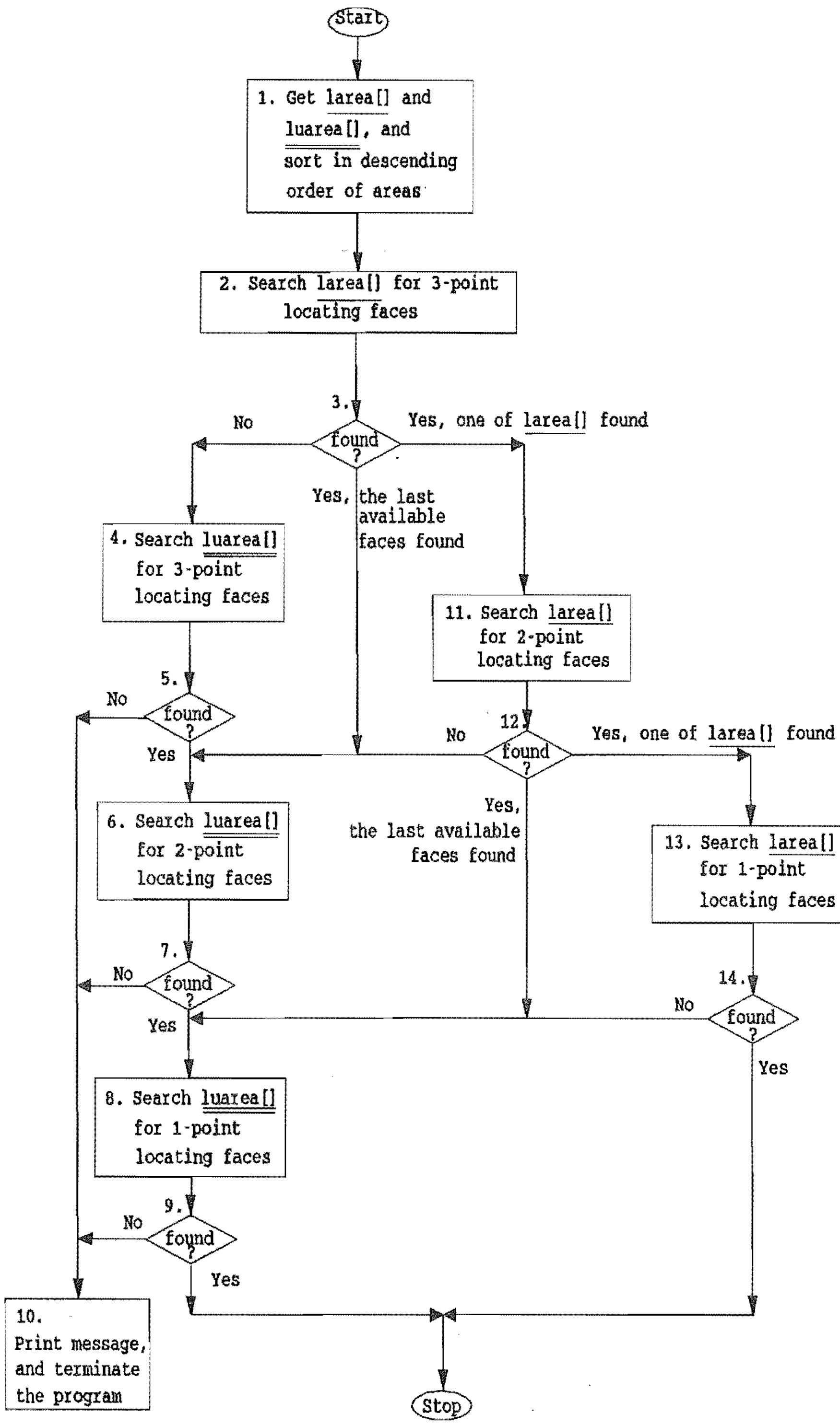


Fig.6.4: Flowchart for determining a location system.

(2) If location system can be partially found -- eg, only 3-point, or 3-point and 2-point locating surfaces -- from the machined surfaces, the search is switched to the unmachined surfaces.

(3) Whenever the lists of the locating surfaces are exhausted and a complete location system can not be found the procedure prints a message and terminates the program.

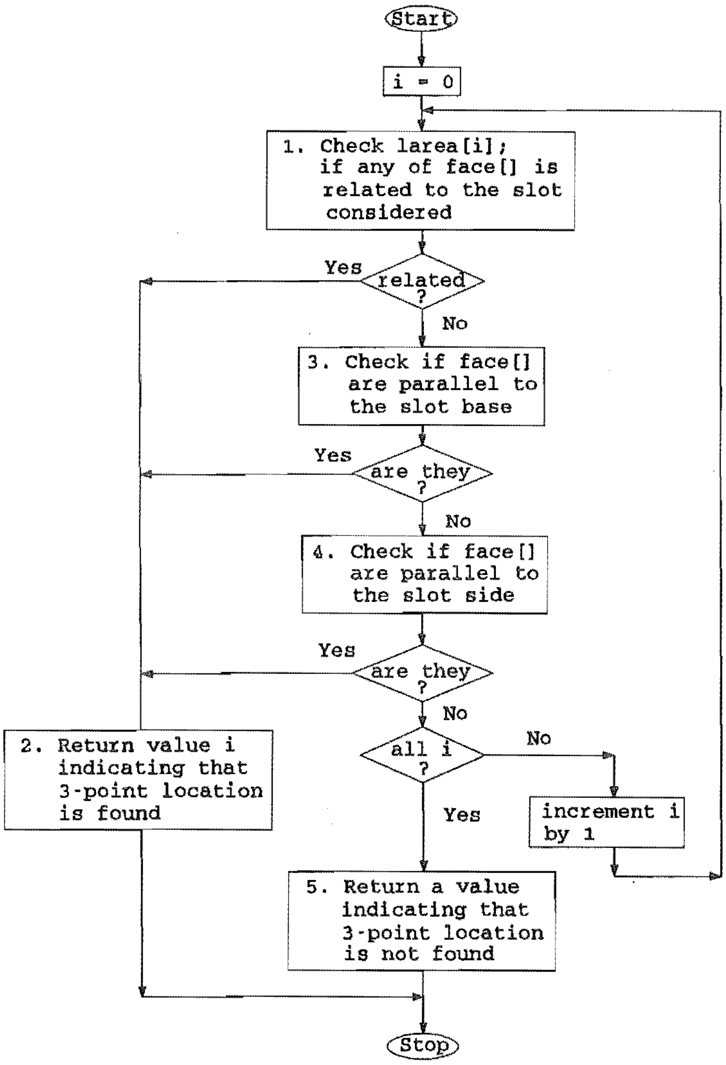


Fig.6.5: Flowchart for determining a locating area for a slot machining.

The procedures for determining 3-point, 2-point and 1-point locating surface are essentially the same. They are based on the same criteria: dimensional relationship, the triangular area, and the position of the surface relative to the feature being machined. As an example, the procedure for determining the 3-point locating surface for machining a slot is shown in Fig.6.5.

This flowchart is the detail of step 2 in Fig.6.4. Starting with array larea[], the procedure checks if it has a locating area that dimensionally relates to the slot being machined. If it does, the coordinates of the area in larea[] are transferred to locating-point array (in this case, locsl3[][][]); otherwise, it will check if that area is opposite to the slot base; if so, the area is chosen; if not, a further check is made. This process goes on until a 3-point locating area is found or not found. In either case, the procedure will return a value signifying the result of the search.

In the case of 2-point location, the procedure will determine the two points from the corner points of the chosen locating surface(s). The two points will be chosen such that the distance between them is maximum. (This is for the presentation only.)

Before the coordinates of a locating area are stored in the corresponding arrays (ie, losl3, losl2, losl1, lost3,..), they are adjusted to avoid ambiguity in identifying a surface (on the output screen or printout). The adjustment is made by shifting the points away from the corner positions. In Fig.6.6, for example, the original 3- point locators are at a, b and c, and after the adjustment the new positions are at a', b' and c' respectively.

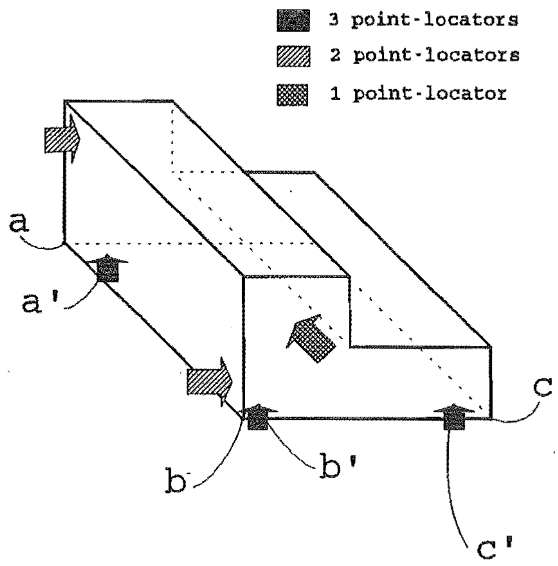


Fig.6.6: Positions of locating symbols.

6.7 Graphical output of a location system

Fig.6.7 shows an example of the screen output resulting from the locating routines. This is the 3-2-1 location system for machining the slot in the bracket in Fig.4.1. The slot is identified by surface numbers 9, 10, and 3. The 3-point locating symbols are on face 14, 2-point on face 6, and 1-point on face 7.

After CAPPFD has completed one location system and before it repeats the same procedure for the next operation, the representation model must be modified so that the model represents the part geometry prior to the operation just considered. For instance, if a slot in Fig.6.7 is machined from a solid stock, then the slot does not exist before this operation, and the model must be modified accordingly.

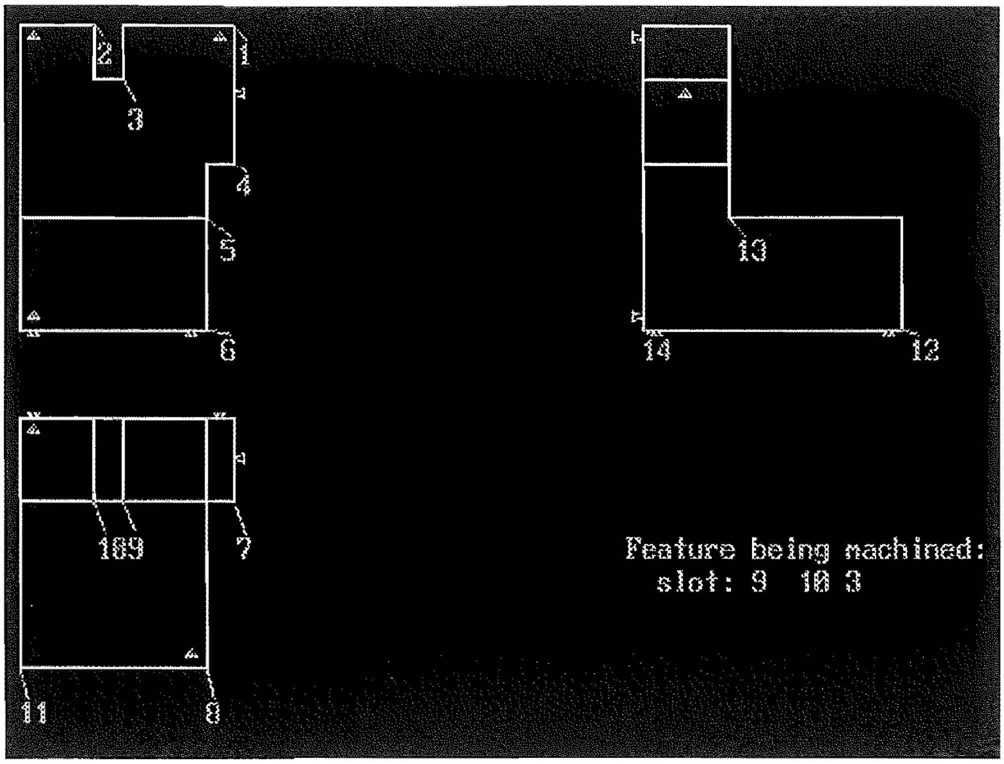


Fig.6.7: Typical screen output for a location system.

6.8 Workpiece model modification

The modification of a workpiece model in CAPPFD is a process of filling numbers in the spatial representation model. Physically, a slot or a step is filled with the amount of metal that is cut away by a machining operation.

The routines for filling a slot and for filling a step were written separately; however, their structure and logic are similar, and only the flowchart for filling a slot is shown here. There are 6 subprograms used directly for filling a slot. Which subprogram to be used depends on the orientation of the slot surfaces. The diagram in Fig.6.8 is the flowchart for filling a slot which has the sides parallel to xy- and xz-planes, and has a base with a normal pointing to the origin. The subprogram requires data on the volumetric boundaries of a slot which are defined by the following variables: cm, cx, rm, rx, dm, and dx (defined in Fig.6.8); these variables are supplied by

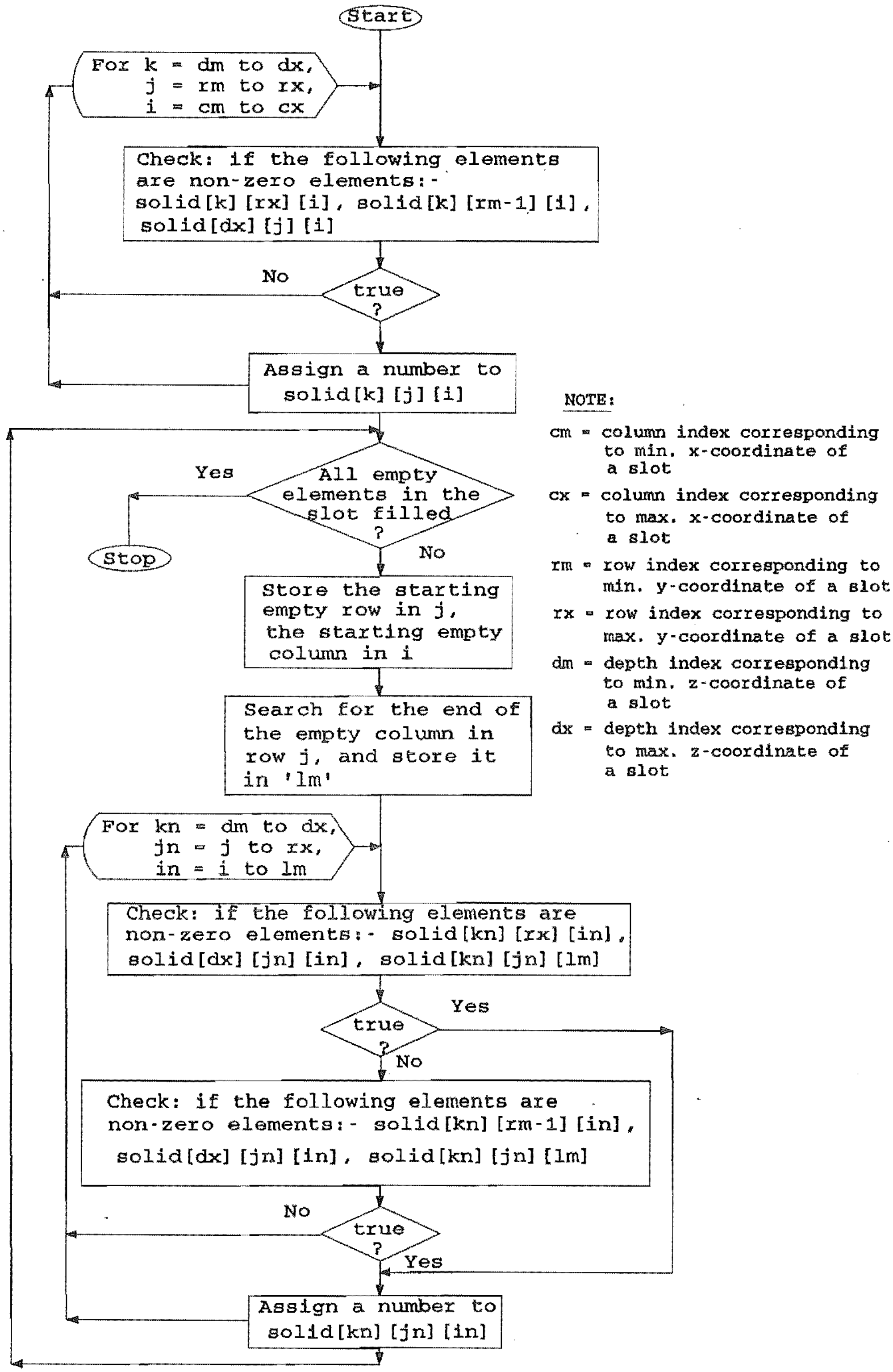
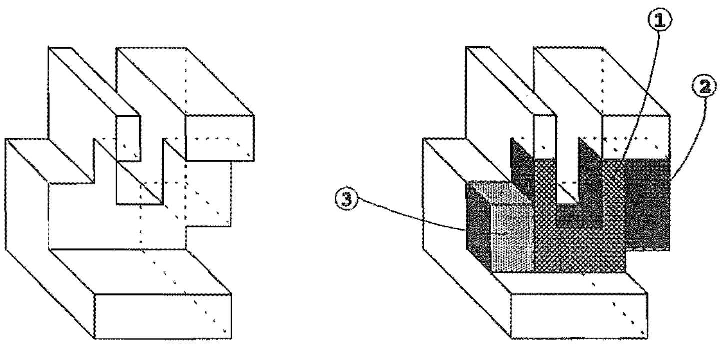


Fig.6.8 Flowchart for filling a slot.

another subprogram.

The flowchart starts with considering the zero elements in the boundaries; if they are surrounded by the sides of the slot, they are assigned a number. Then it checks if the slot is completely filled. If so, the process stops; otherwise, it goes on filling the numbers. These steps can be illustrated by Fig.6.9 where the sequence of metal filling is: 1, 2, 3.

Fig.6.10 shows a typical complexity of a step that the system can handle. It is assumed that all the steps, except the one being filled, have been processed previously.



(a) Before metal filling (b) After metal filling

Fig.6.9: Steps in filling a slot.

In the case of a facing operation, there is no change in the workpiece geometry, and no modification in the model is made; the surfaces before and after the operations have the same identification numbers.

6.9 Preparing data for the next search

When the workpiece model changes from one operation to the next, the surface numbers also change. This is because some surfaces are

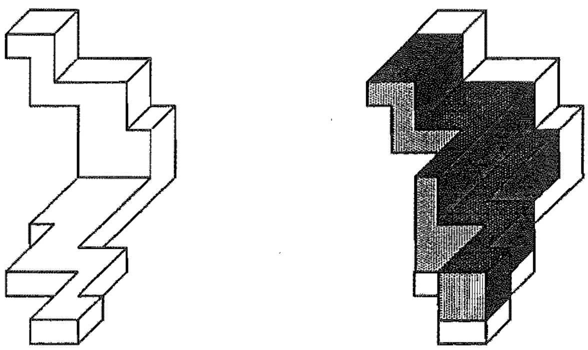
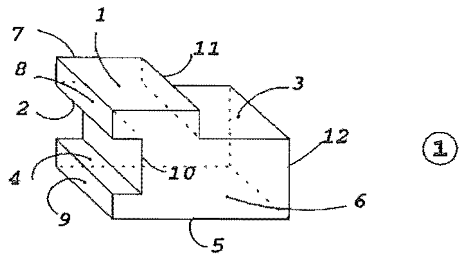


Fig.6.10: Metal filling of a step.

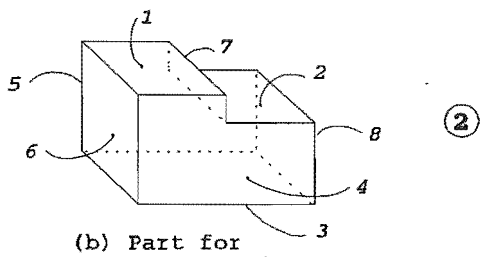
combined and some are eliminated. Therefore, it is essential to keep track of the changes of these surface numbers. CAPPFD uses a two-dimensional array, named track[][], to record the changes. It is created after the sequencing of operations is completed. Fig.6.11 illustrates the idea of storing the surface numbers in the array. The numbers circled indicate the sequence of locating the workpiece. The surface numbers in column 1 belong to the finished part which are used for locating the workpiece in the last operation; those in column 2 are for, the second last, and so on. Note that a zero is used for the array element to indicate that the particular surface does not exist.

CAPPFD uses this array to modify the surface numbers in the arrays involved in the search for a location system for the following operation. These arrays include the feature arrays (sloting[][], stepc[][], facing[][]), relationship arrays (relsl, relst, relfc), machined surface array (mcf[]), and unmachined surface array (unmac[][]).

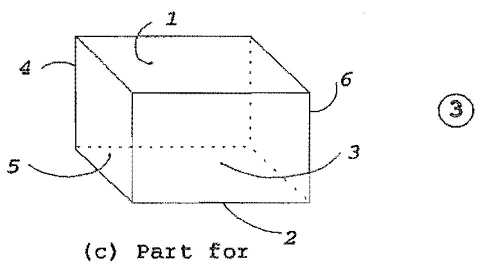
In the end, these arrays will contain the surface numbers corresponding to those of the stock. But, in drawing the tolerance charts, which is the final



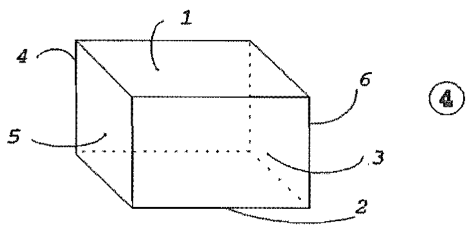
(a) Finished part
for slotting



(b) Part for
step cutting



(c) Part for
facing the
top face



(d) Stock part

	①	②	③	④
i \ j	0	1	2	3
0	1	1	1	1
1	2	0	0	0
2	3	2	0	0
3	4	0	0	0
4	5	3	2	2
5	6	4	3	3
6	7	5	4	4
7	8	6	5	5
8	9	6	5	5
9	10	0	0	0
10	11	7	0	0
11	12	8	6	6

(e) track[] []

Fig.6.11 The changes of model surfaces.

step of the program, the original surface numbers are required for some of these arrays. Therefore, a temporary storage is provided for storing these surface numbers before the execution of locating module, and, afterwards, they are re-stored back, to the original arrays, for the charting module.

6.10 Conclusion

The procedure for locating the workpiece during machining is based on both geometric control and dimensional control. All surfaces that are candidates for being a locating surface are considered in order of their degree of geometric control --the triangular locating areas, and in choosing a candidate, the procedure gives a higher priority to one with a higher requirement for dimensional control. That is, CAPPFD tries to maintain dimensional control with the highest probability of achieving the best geometric control.

7. TOLERANCE CHARTING IN CAPPFD

Most computerised tolerance charting packages are limited to rotational parts, which can be described by a two dimensional model, and only one chart is normally required. Although the idea of charting the machining sequence on a prismatic part is not new, so far there has not been a published report on an attempt to computerize it. The CAPPFD system is capable of producing the tolerance charts for all machined surfaces on a prismatic part. At present, linear dimensional tolerances only are allowed.

The charting module in CAPPFD is a result of integrating the tolerance charting program, discussed in chapter 2, with the sequencing package. This chapter discusses some of the important details of the integration.

7.1 Tolerance chart module

Fig.7.1 shows the flowchart for tolerance charting in the tolerance chart module. This flowchart is basically similar to the one in Fig.2.6 except that it has three new functions added. They are:

(1) **A program loop for repeating execution:** This enables CAPPFD to produce three tolerance charts for a particular part. Each time the loop is executed, it produces a tolerance chart for all machining cuts made on the surfaces perpendicular to a principal plane defined in the spatial representation model (section 4.1). After the execution is completed, a new set of data is required for the next loop execution.

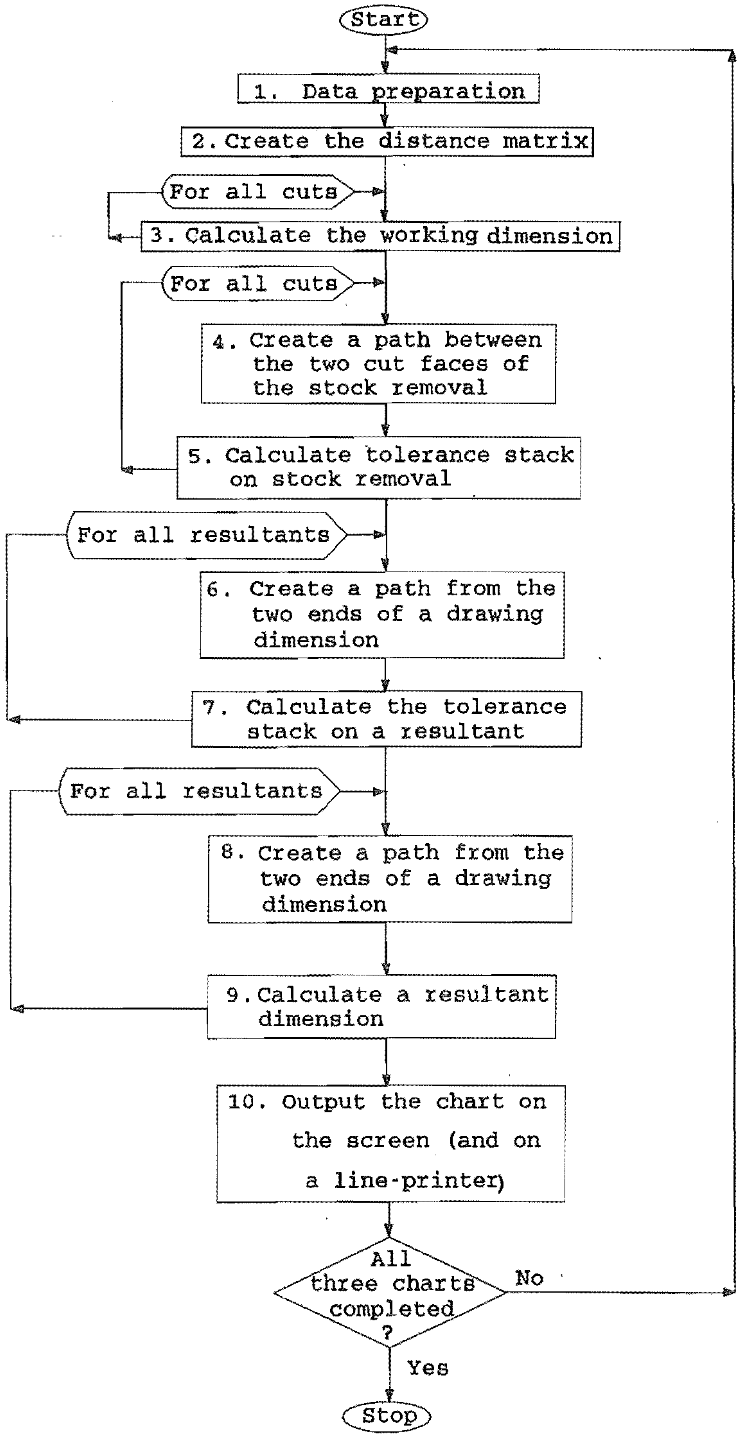


Fig.7.1: Flowchart for tolerance chart construction.

(2) **The data preparation function:** This function embraces the selection and organization of the data so that they can be used for charting. In the following section the detail of steps in preparing the data will be discussed further.

(3) **The chart drawing function:** This function is to draw the tolerance charts on the screen; it is mainly supported by the subprograms in the support module.

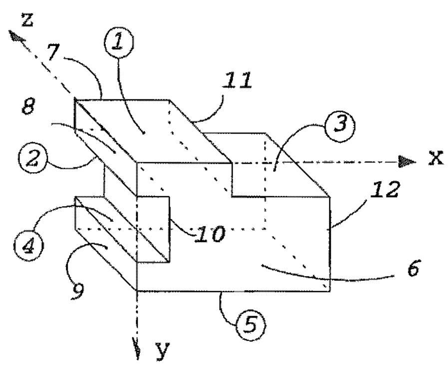
7.2 Data preparation for tolerance chart module

On a rotational machined part, the cut and locating edges that establish the length dimensions are perpendicular to the work axis. Since diametral dimensions are not normally charted, only one tolerance chart is required. But, in the case of a prismatic part, where no axis of symmetry exists, the machined surfaces contribute to length dimensions and tolerances in more than one plane. Consequently, more than one chart is required for analysing all dimensions.

To construct a tolerance chart for a set of dimensions, the tolerance chart module needs only the data relevant to the dimensions. But, in operations like step cutting or slotting, the surfaces in more than one plane are cut, and there are three locating faces. As each machining cut in the chart requires only one machined surface and one locating face, those unrelated surfaces must be screened out.

The screening process in CAPPFD makes use a two-dimensional array of integers, called map[][], which is temporarily created for each chart. This array stores the surface numbers on different levels of the spatial representation model. Fig.7.2 illustrates an example of what is stored in the array when the tolerance chart is to be constructed for the dimensions on the surfaces parallel to xz-plane. To get the machined surfaces for all cuts, the feature arrays are called sequentially (facing[][], stepc[][], sloting[][]): their elements are then compared with the array map[][]; if there is a match, the row index of the match is converted to a capital letter and stored in the cut-face array (cut[]). The same procedure is also applied to storing the end faces of stock and drawing dimensions, and the locating faces (ie, in mdf[], mdt[], dwf[], dwt[], loc[]).

Other data such as the dimensions and tolerances of the drawing, and the tolerances of the stock dimensions, are also based on matching surface numbers as described above in transferring from the 'production data' to the tolerance chart data (ie, dbas[], dtol[], and stol[]). Fig.7.3 illustrates the steps for retrieving the drawing data for charting, from the production data.



(a) finished part

i \ j	0	1	2	3	4
0	1	0	0	0	0
1	2	3	0	0	0
2	4	0	0	0	0
3	5	0	0	0	0

(b) map[i][j]

Fig.7.2: Face numbers in map[][].

Note that the row indices in map[][] correspond to the vertical lines identifying the surfaces in the tolerance chart (see Fig.2.1). These lines are always labelled alphabetically from the origin of the model. This is a reason for making map[][] a two dimensional array.

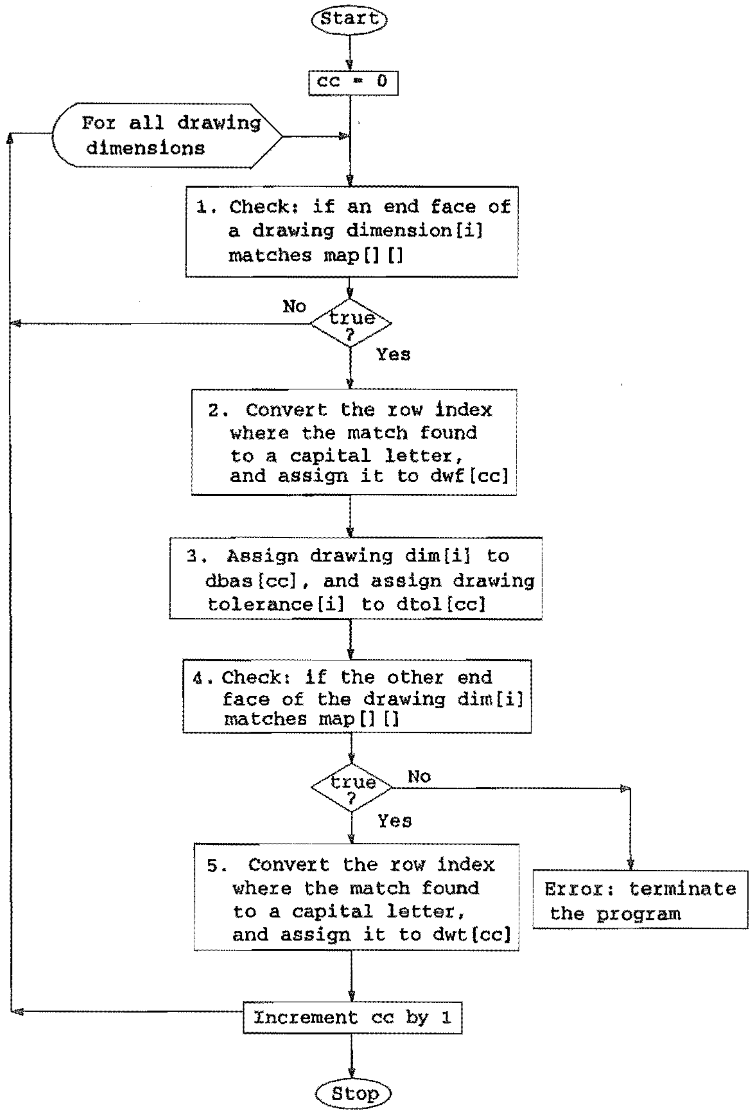


Fig.7.3: Flowchart for retrieving blueprint data.

The procedure for preparing the cutting data for each operation; such as, the surface to be cut, the locating surface, the machining tolerance, and the amount of metal to be removed, depends on the type of machining operation. In charting a facing or a step cutting operation only one line is required to identify the cut in the chart; therefore, the data relevant to the cut can be readily retrieved from the production data. But in charting a slotting operation where the two sides of a slot are charted, two lines of cut are required, and they are treated as two different cuts in the chart as illustrated in Fig.7.4. In this case, the procedure must supply the data for the extra cut, which can occur simultaneously with the other in some cases. Also shown in the figure are two methods of charting a slot: (a) when the locating face is lower than the cut face, and (b) when it is higher. The reasons for them are: firstly, in setting up the cutter, the cutter side which is closer to the locating face is used. Consequently, the arrow head of the cut symbol in the chart points to the side of the slot closer to the locating face. Secondly, the width of the slot is either a copy of the cutter width or a result of the movement of the cutter to a stop. In both cases, the closer side determines the position of the other side; therefore it should be the reference of the other side.

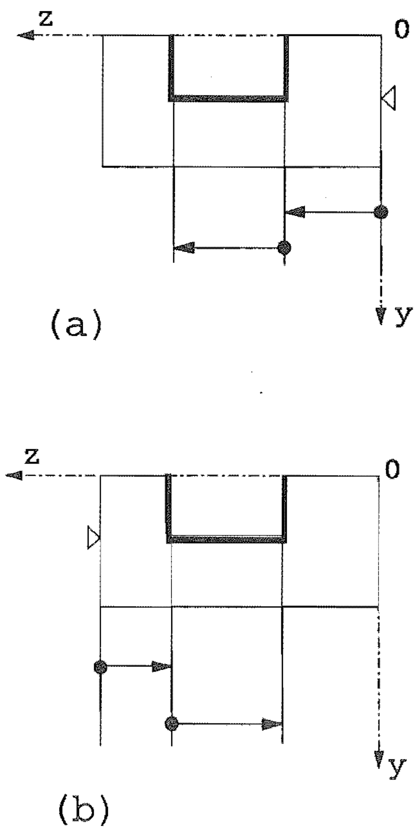


Fig.7.4: Charting a slot.

Fig.7.5 and Fig.7.6 show the procedure for retrieving the cutting data from slotting operations. The flowchart in Fig.7.5 is for the case when the cut surface is the bottom face of a slot. As each cut is represented by one line in the tolerance chart, the transformation of data is straight forwards; the metal

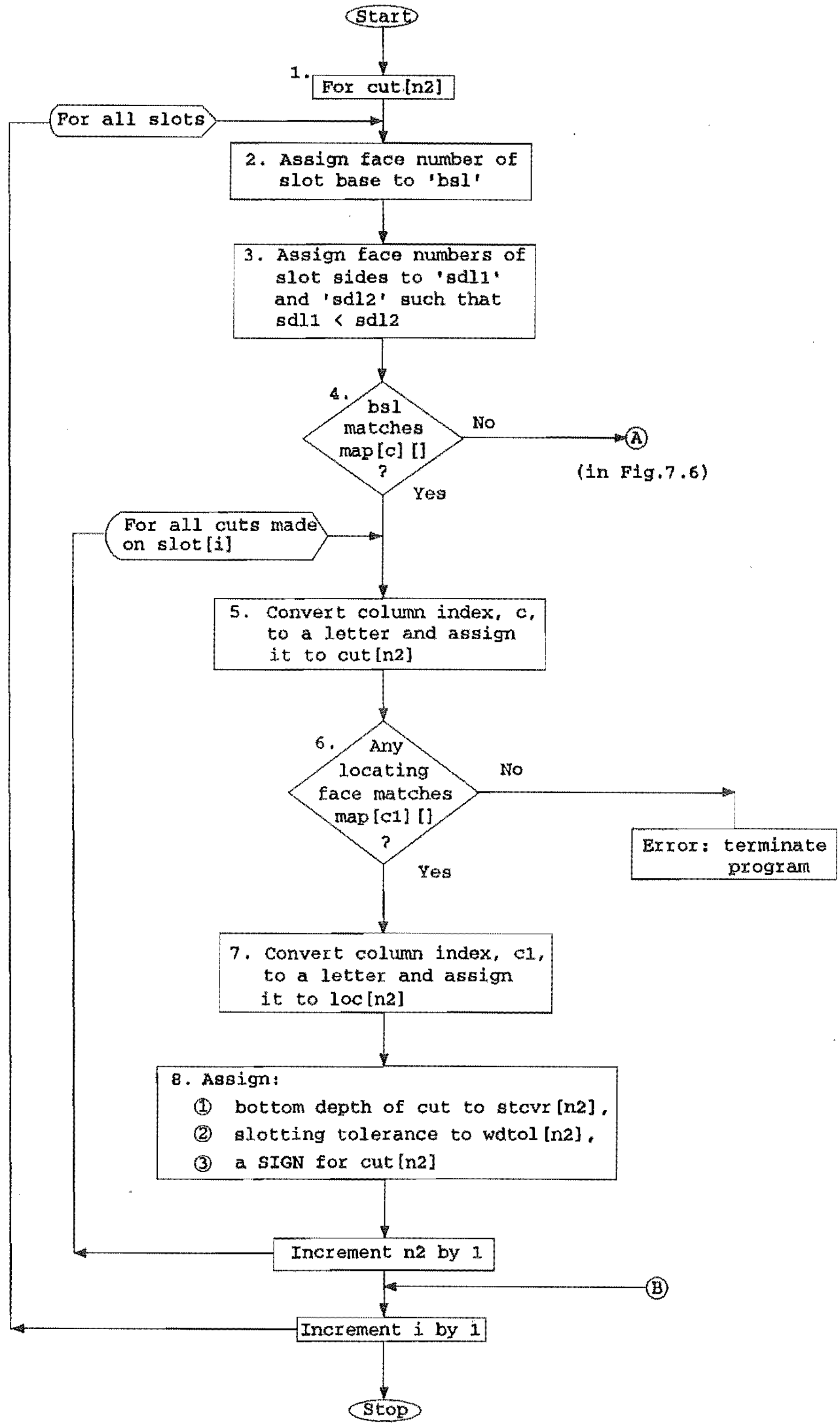


Fig.7.5: Retrieving chart data from slotting operations.

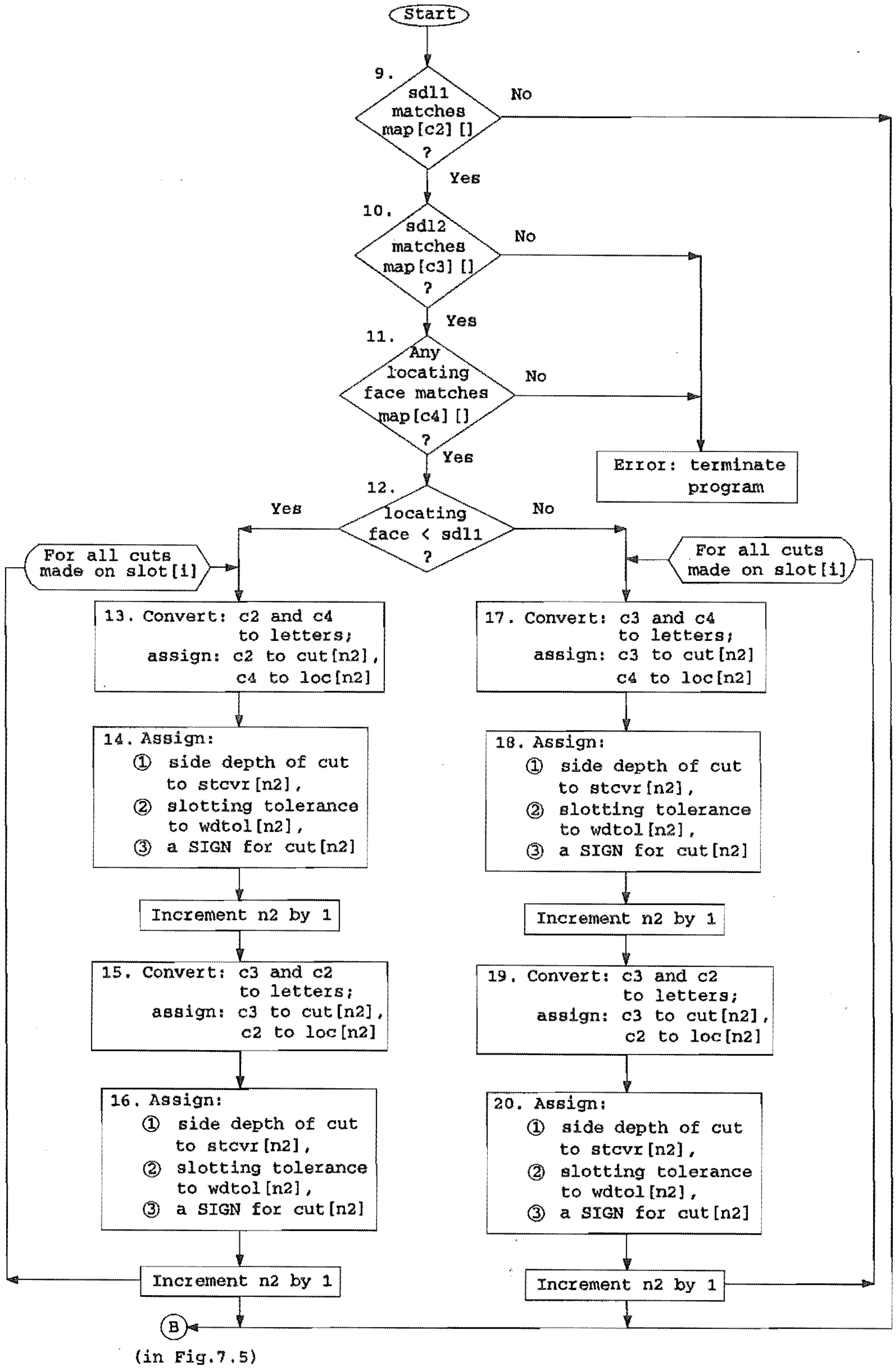


Fig.7.6: Retrieving chart data from slotting operations (cont.)

removal dimensions are equal to the corresponding bottom depths of cut. The machining tolerances are assigned to all cuts depending on the type of the cut: roughing or finishing. This information is included in the values of machining tolerances input by the user. Fig.7.6 shows the logic of transformation of data for charting the sides of a slot. The flowchart can be divided into two parts corresponding to Fig.7.4(a) and (b).

The steps for getting the chart data for the facing and the step cutting operations are not shown here because they are similar in structure and logic to Fig.7.5.

7.3 Sign convention for machining cuts

In the calculation of working dimensions, as discussed in chapter 2, a variable, SIGN, is used to identify if a machining cut produces a shorter or a longer processing dimension. The value of this variable is either -1, for the former, and +1 for the latter. In the original charting program the value of SIGN for each cut is input by the user.

Since CAPPFD provides storage for the directions of all surface normals on a machined part (section 4.2), this information together with the positions of the cuts and of the locating faces relative to the origin of the part model is used as a basis for assigning a sign value (+1 or -1) to a machining cut.

CAPPFD stores the sign values of all machining cuts for a tolerance chart in a one-dimensional array, named 'sign[]'. To derive the rules for assigning the values, consider Fig.7.7. The machining cuts shown here are not in any particular order; they are only representative of all the possible combinations of cut and locating faces. The origin of the part model is assumed to be on the left edge of the sketch. From this partial tolerance

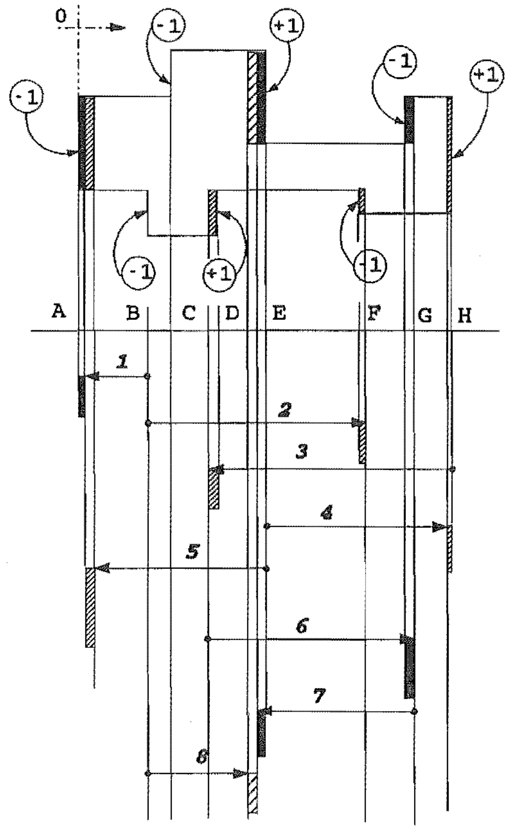


Fig.7.7: Possible combinations of cut and locating faces.

chart, the value of sign each machining cut could be established using the rules shown in the extended-entry decision table of Fig.7.8(a). This table may be transformed to the limited-entry table shown in Fig.8(b), which is used in the subroutine for assigning a sign value to a machining cut.

direction of cut face	-1	-1	+1	+1	-1	-1	+1	+1
direction of locating face	-1	-1	+1	+1	+1	+1	-1	-1
position of locating face relative to cut face	* l>c	c>l	l>c	c>l	l>c	c>l	l>c	c>l
sign of the cut	-1	+1	+1	-1	-1	+1	+1	-1

(a) Extended-entry table

l = -1	1	0	0	1	1	0	0	1
c = -1	1	0	1	0	1	0	1	0
l>c	1	0	0	1	0	1	1	0
SIGN=-1	X	X	X	X				
SIGN=+1					X	X	X	X

(b) Limited-entry table

NOTE: * l = locating face, c = cut face

Fig.7.8: Decision tables for sign convention.

7.4 Calculation and drawing routines

The logic of the calculation routine is the same as that described in chapter 2. The drawing routine consists of the subroutines for drawing the part sketch, writing the headings, drawing the cutting and locating symbols, and filling the chart with numbers. In the first loop of execution of the tolerance chart module, the part sketch is drawn using the coordinates of the surfaces parallel to yz-plane, and the dimensions charted are of the surfaces parallel to xz-plane; in the second loop, the part sketch is drawn using the same coordinates as for the first loop, but the dimensions charted belong to the surfaces parallel to xy-plane; in the third loop, the part sketch is drawn using the coordinates of the surfaces parallel to xy-plane, and the dimensions charted are of the surfaces parallel to yz-plane.

After each loop, the data are changed, and a new tolerance chart is produced on the screen. Fig.7.9 shows a typical screen output of the tolerance chart.

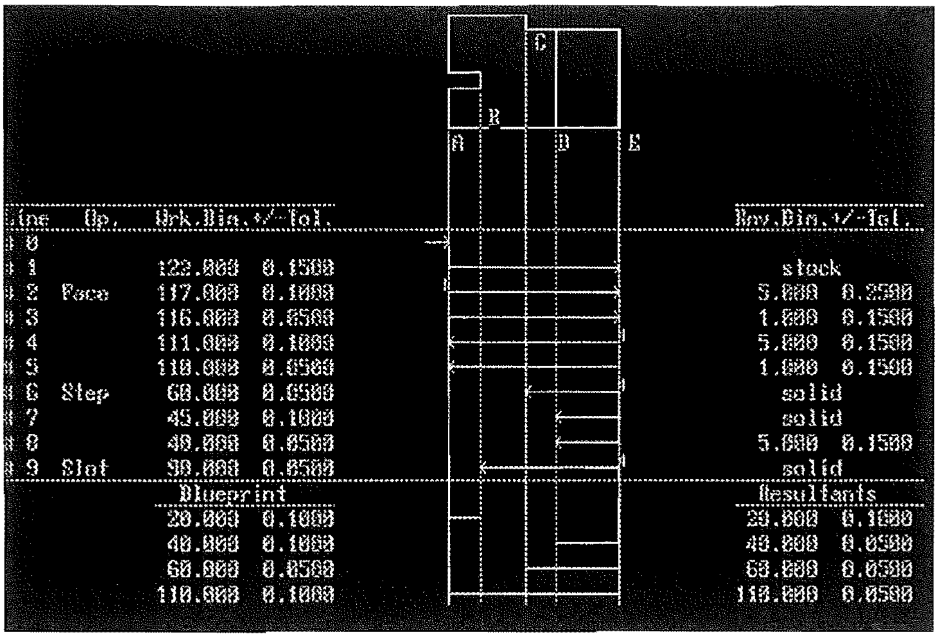


Fig.7.9: Typical screen output of tolerance chart.

7.5 Conclusion

CAPPFD is capable of producing tolerance charts for each of the three dimensional planes of a workpiece. All data for tolerance charting are transformed from the input data. CAPPFD makes use of a two dimensional array to screen out the surfaces that are not relevant to a particular chart. It is also capable of automatically identifying if a machined cut shortens or lengthens a processing dimension. The integrating concepts discussed in this chapter could be applied to other CAPP systems, provided the system incorporates a method for identifying the directions of the surface normals.

8. RUNNING THE CAPPFD SYSTEM

In this chapter guidelines for running the CAPPFD system are given. The general steps of using the system are listed as follows:

(1) prepare the spatial representation data of the machined part,
(2) compile and link all the modules,
(3) execute the program,
(4) enter (or edit) the production data,
(5) interact with the system to print the output on the line-printer.

These steps are demonstrated by the following two examples. In Example 1 the production data are interactively input into the system through a dialogue. Example 2 assumes the data are already stored in a data file, the contents of this data file being given.

8.1 Example 1

(1) Model data file:

The specifications of the machined part are given in the drawing, Fig.8.1. From these specifications the spatial matrix representation of the part is developed (see Fig.4.2) and stored in a data file. Fig.8.2 shows the contents of this data file. The first line gives the numbers of depths, rows, and columns of the spatial representation. This is followed by the matrices arranged in an increasing order of the depths.

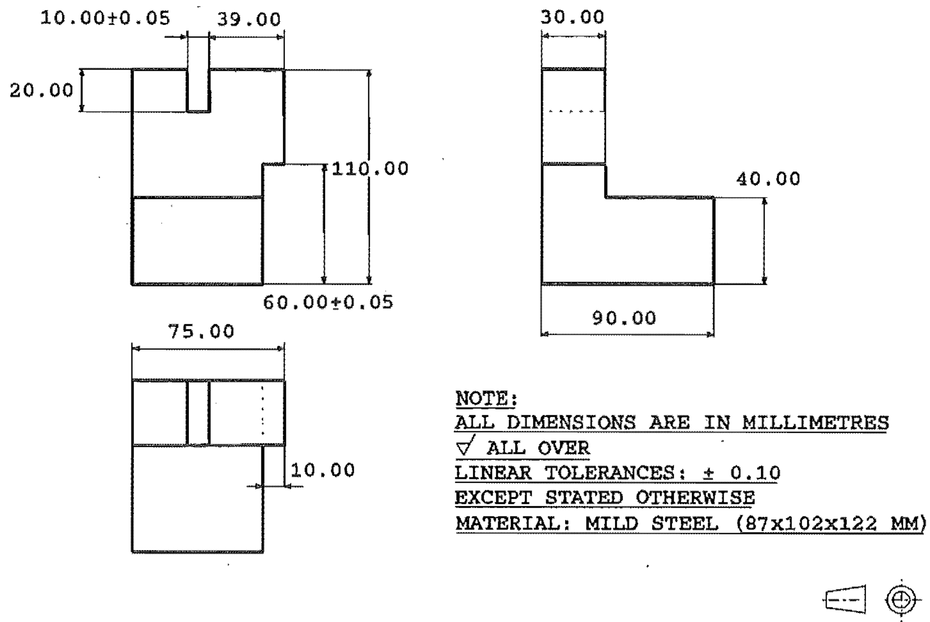


Fig.8.1 Drawing of a bracket.

(1) Starting up the system:

All modules are compiled and linked by a batch file, 'clp.bat'. This produces an executable file, 'pfd.exe'. To run the system, simply type 'pfd', or 'pfd' followed by the name of the spatial representation file as follows: pfd wm10.dat <cr>. Here the data file is wm10.dat.

(3) Data input:

The session for input of the production data starts with the screen display as shown in Fig.8.3. When 'p' is entered, the screen in Fig.8.4 is printed on the line-printer. (It should be noted that this command is also used to dump any graphics screen to the printer.) This printout is used for identifying the surface numbers of the part, which are required for data input. CAPPFD then asks for a file name for storing the data. After this, the dialogue for input of the production data starts.

Table 8.1: Summary of machining sequence.

No.	Oper.	Cut and locating surface numbers			
		Cut	3-point	2-point	1-point
1	facing	6	11	14	1
2	"	7	6	11	12
3	"	14	7	6	12
4	"	1	7	14	6
5	"	11	7	14	6
6	"	12	7	14	1
7	step cut	4, 8	11	14	6
8	"	5, 13	11	14	6
9	slotting	9, 10, 3	14	6	7

Fig.8.5 show the dialogue for data input. The items underlined are entered by the user. If errors are made in entering the data during this dialogue, they can be corrected during the editing session after the dialogue.

(4) Output of machining sequence:

After the data input and editing session, a series of process pictures showing the 3-2-1 location systems for all operations are displayed on the screen. They are shown in Fig.8.6 to Fig.8.14. As mentioned before, the actual machining sequence is the reverse of the order shown on the screen. The sequence of machining operations is summarised in Table 8.1.

(5) Output of tolerance charts:

Fig.8.15 to 8.17 show the tolerance charts from the system. These charts are slightly different from that shown in Fig.2.1. To simplify the graphics, no 'dot' is used in the cut symbols, and the column for the letters identifying cut faces have been omitted.

```
 8   7   7
  0.0  20.0  40.0  60.0  70.0  80.0  90.0
 20.0   0.0   0.0   0.0   0.0   0.0   0.0
 50.0   0.0   0.0   0.0   0.0   0.0   0.0
 60.0   0.0   0.0   0.0   0.0   0.0   0.0
 70.0   0.0   0.0   0.0   0.0   0.0   0.0
 80.0   0.0   0.0   0.0   0.0   0.0   0.0
110.0   0.0   0.0   0.0   0.0   0.0   0.0

 10.0  20.0  40.0  60.0  70.0  80.0  90.0
 20.0   0.0   0.0   0.0  99.0  99.0  99.0
 50.0   0.0   0.0   0.0  99.0  99.0  99.0
 60.0   0.0   0.0   0.0   0.0   0.0   0.0
 70.0   0.0   0.0   0.0   0.0   0.0   0.0
 80.0   0.0   0.0   0.0   0.0   0.0   0.0
110.0   0.0   0.0   0.0   0.0   0.0   0.0

 30.0  20.0  40.0  60.0  70.0  80.0  90.0
 20.0   0.0   0.0   0.0  99.0  99.0  99.0
 50.0   0.0   0.0   0.0  99.0  99.0  99.0
 60.0   0.0   0.0   0.0  99.0  99.0  99.0
 70.0   0.0   0.0   0.0  99.0  88.0  99.0
 80.0  99.0  99.0  99.0  99.0  99.0  99.0
110.0  99.0  99.0  99.0  99.0  99.0  99.0

 35.0  20.0  40.0  60.0  70.0  80.0  90.0
 20.0   0.0   0.0   0.0  99.0  99.0  99.0
 50.0   0.0   0.0   0.0  99.0  99.0  99.0
 60.0   0.0   0.0   0.0  99.0  99.0  99.0
 70.0   0.0   0.0   0.0  99.0  99.0  99.0
 80.0  99.0  99.0  99.0  99.0  99.0  99.0
110.0  99.0  99.0  99.0  99.0  99.0  99.0

 39.0  20.0  40.0  60.0  70.0  80.0  90.0
 20.0   0.0   0.0   0.0  99.0  99.0  99.0
 50.0   0.0   0.0   0.0  99.0  99.0  99.0
 60.0   0.0   0.0   0.0  99.0  99.0  99.0
 70.0   0.0   0.0   0.0  99.0  99.0  99.0
 80.0  99.0  77.0  99.0  99.0  99.0  99.0
110.0  99.0  77.0  99.0  99.0  99.0  99.0

 49.0  20.0  40.0  60.0  70.0  80.0  90.0
 20.0   0.0   0.0   0.0   0.0   0.0   0.0
 50.0   0.0   0.0   0.0  99.0  99.0  99.0
 60.0   0.0   0.0   0.0  99.0  99.0  99.0
 70.0   0.0   0.0   0.0  99.0  99.0  99.0
 80.0  99.0  77.0  99.0  99.0  99.0  99.0
110.0  99.0  77.0  99.0  99.0  99.0  99.0

 55.0  20.0  40.0  60.0  70.0  80.0  90.0
 20.0   0.0   0.0   0.0  99.0  99.0  99.0
 50.0   0.0   0.0   0.0  99.0  99.0  99.0
 60.0   0.0   0.0   0.0  99.0  99.0  99.0
 70.0   0.0   0.0   0.0  99.0  99.0  99.0
 80.0  99.0  77.0  99.0  99.0  99.0  99.0
110.0  99.0  77.0  99.0  99.0  99.0  99.0

 75.0  20.0  40.0  60.0  70.0  80.0  90.0
 20.0   0.0   0.0   0.0  99.0  99.0  99.0
 50.0   0.0   0.0   0.0  99.0  99.0  99.0
 60.0   0.0   0.0   0.0  99.0  99.0  99.0
 70.0   0.0   0.0   0.0  99.0  99.0  99.0
 80.0  99.0  99.0  99.0  99.0  99.0  99.0
110.0  99.0  99.0  99.0  99.0  99.0  99.0
```

Fig.8.2: Part model representation.

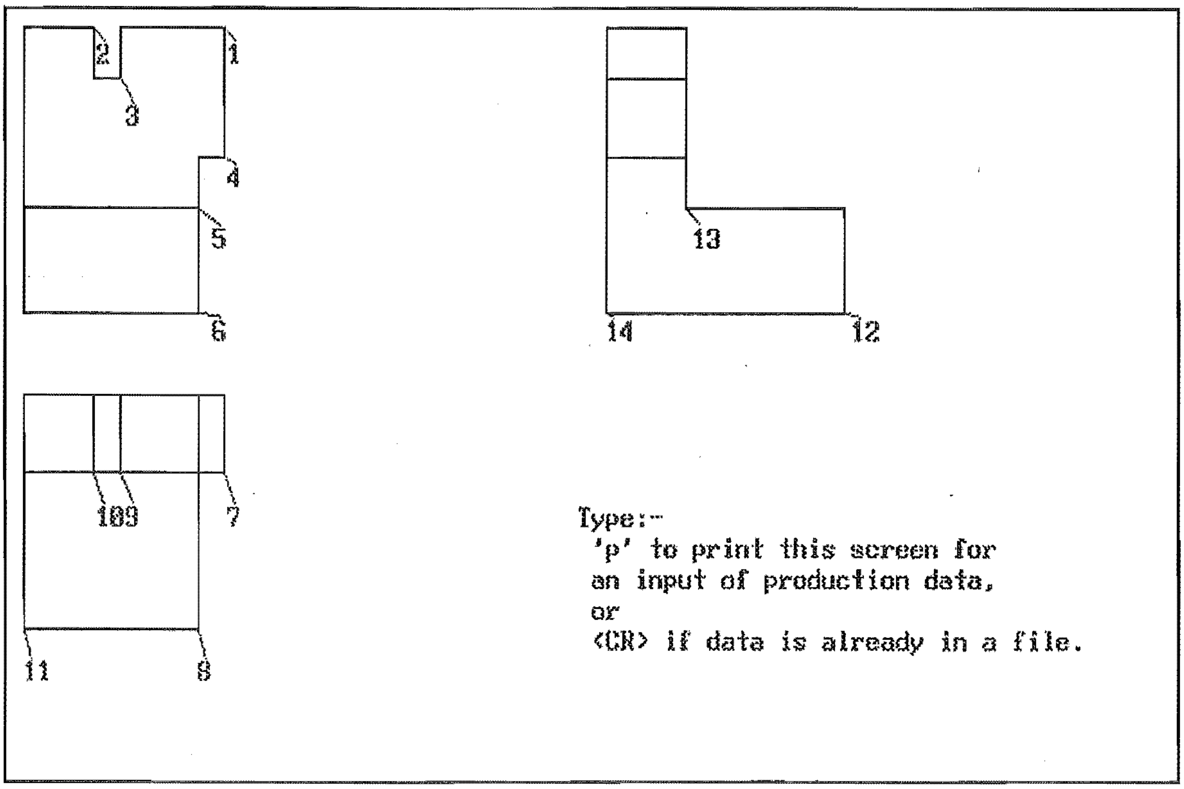


Fig.8.3: The first screen display of the part.

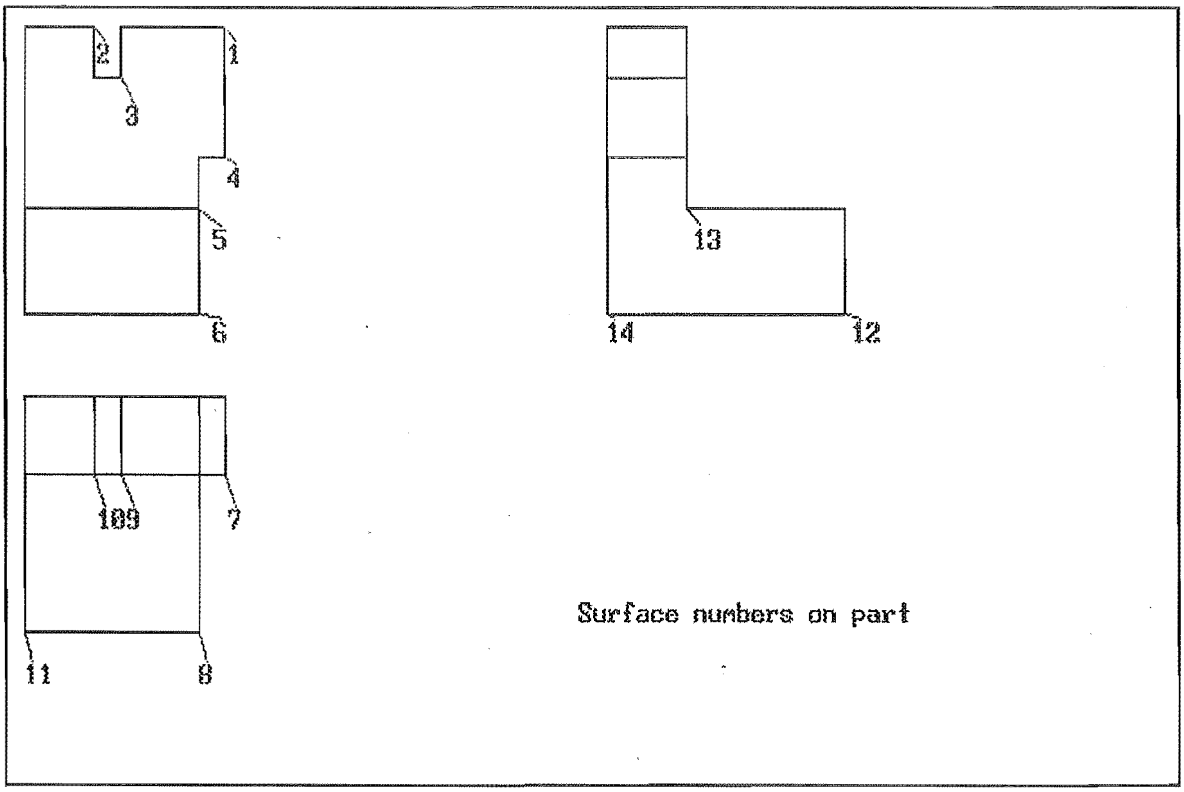


Fig.8.4: Surface numbers on the part.

```
Enter file name for storing data: prod.dat

Number of stock dimensions
(type 0 if no stock dimemsion): 3
Enter stock dimensions:-
# 1:- stk. dim. from: 1
      stk. dim. to   : 6
      tolerance(mm): 0.15
# 2:- stk. dim. from: 7
      stk. dim. to   : 11
      tolerance(mm): 0.15
# 3:- stk. dim. from: 12
      stk. dim. to   : 14
      tolerance(mm): 0.15

Number of drawing dimensions: 10
Enter drawing dimensions:-
# 1:- dwg. dim. from: 7
      dwg. dim. to   : 9
      dimension(mm): 39.00
      tolerance(mm): 0.10
# 2:- dwg. dim. from: 9
      dwg. dim. to   : 10
      dimension(mm): 10.00
      tolerance(mm): 0.05
# 3:- dwg. dim. from: 2
      dwg. dim. to   : 3
      dimension(mm): 20.00
      tolerance(mm): 0.10
# 4:- dwg. dim. from: 6
      dwg. dim. to   : 5
      dimension(mm): 40.00
      tolerance(mm): 0.10
# 5:- dwg. dim. from: 6
      dwg. dim. to   : 4
      dimension(mm): 60.00
      tolerance(mm): 0.05
# 6:- dwg. dim. from: 6
      dwg. dim. to   : 1
      dimension(mm): 110.00
      tolerance(mm): 0.10
# 7:- dwg. dim. from: 8
      dwg. dim. to   : 7
      dimension(mm): 10.00
      tolerance(mm): 0.10
# 8:- dwg. dim. from: 11
      dwg. dim. to   : 7
      dimension(mm): 75.00
      tolerance(mm): 0.10
# 9:- dwg. dim. from: 13
      dwg. dim. to   : 14
      dimension(mm): 30.00
      tolerance(mm): 0.10
# 10:- dwg. dim. from: 12
      dwg. dim. to   : 14
      dimension(mm): 90.00
      tolerance(mm): 0.10
```

Fig.8.5: Dialogue for data input.

```
Enter the number of facing operations
      (type 0 if no facing operation): 6
facing #1:- (type 0 to stop)
 on surface: 12
 on surface: 0
  number of cuts: 2
   cut # 1: depth of cut (mm): 5.00
            mc tolerance (mm): 0.10
   cut # 2: depth of cut (mm): 1.00
            mc tolerance (mm): 0.05
facing #2:- (type 0 to stop)
 on surface: 6
 on surface: 0
  number of cuts: 2
   cut # 1: depth of cut (mm): 5.00
            mc tolerance (mm): 0.10
   cut # 2: depth of cut (mm): 1.00
            mc tolerance (mm): 0.05
facing #3:- (type 0 to stop)
 on surface: 11
 on surface: 0
  number of cuts: 2
   cut # 1: depth of cut (mm): 5.00
            mc tolerance (mm): 0.10
   cut # 2: depth of cut (mm): 1.00
            mc tolerance (mm): 0.05
facing #4:- (type 0 to stop)
 on surface: 7
 on surface: 0
  number of cuts: 2
   cut # 1: depth of cut (mm): 5.00
            mc tolerance (mm): 0.10
   cut # 2: depth of cut (mm): 1.00
            mc tolerance (mm): 0.05
facing #5:- (type 0 to stop)
 on surface: 14
 on surface: 0
  number of cuts: 2
   cut # 1: depth of cut (mm): 5.00
            mc tolerance (mm): 0.10
   cut # 2: depth of cut (mm): 1.00
            mc tolerance (mm): 0.05
facing #6:- (type 0 to stop)
 on surface: 1
 on surface: 2
 on surface: 0
  number of cuts: 2
   cut # 1: depth of cut (mm): 5.00
            mc tolerance (mm): 0.10
   cut # 2: depth of cut (mm): 1.00
            mc tolerance (mm): 0.05
```

Fig.8.5: (cont.)

```
Enter the number of steping operations
      (type 0 if no steping operation): 2
step cuting #1:- (type 0 to stop)
 on surface: 4
 on surface: 8
 on surface: 0
   number of cuts: 1
 cut # 1:
          is made on: (1) solid stock, or (2) formed step: 1
               m/c tolerance (mm): 0.05
step cuting #2:- (type 0 to stop)
 on surface: 5
 on surface: 13
 on surface: 0
   number of cuts: 2
 cut # 1:
          is made on: (1) solid stock, or (2) formed step: 1
               m/c tolerance (mm): 0.10
 cut # 2:
         bottom depth of cut (mm): 5.00
           side depth of cut (mm): 5.00
               m/c tolerance (mm): 0.05

Enter the number of sloting operations
      (type 0 if no sloting operation): 1
sloting #1:- (type 0 to stop)
 on surface: 9
 on surface: 10
 on surface: 3
 on surface: 0
 slot opening faces:- (type 0 to stop)
  opening face: 1
  opening face: 2
  opening face: 0
 number of cuts: 1
 cut # 1:
          is made on: (1) solid stock, or (2) formed slot: 1
                m/c tolerance (mm): 0.05
```

Fig.8.5: (cont.)

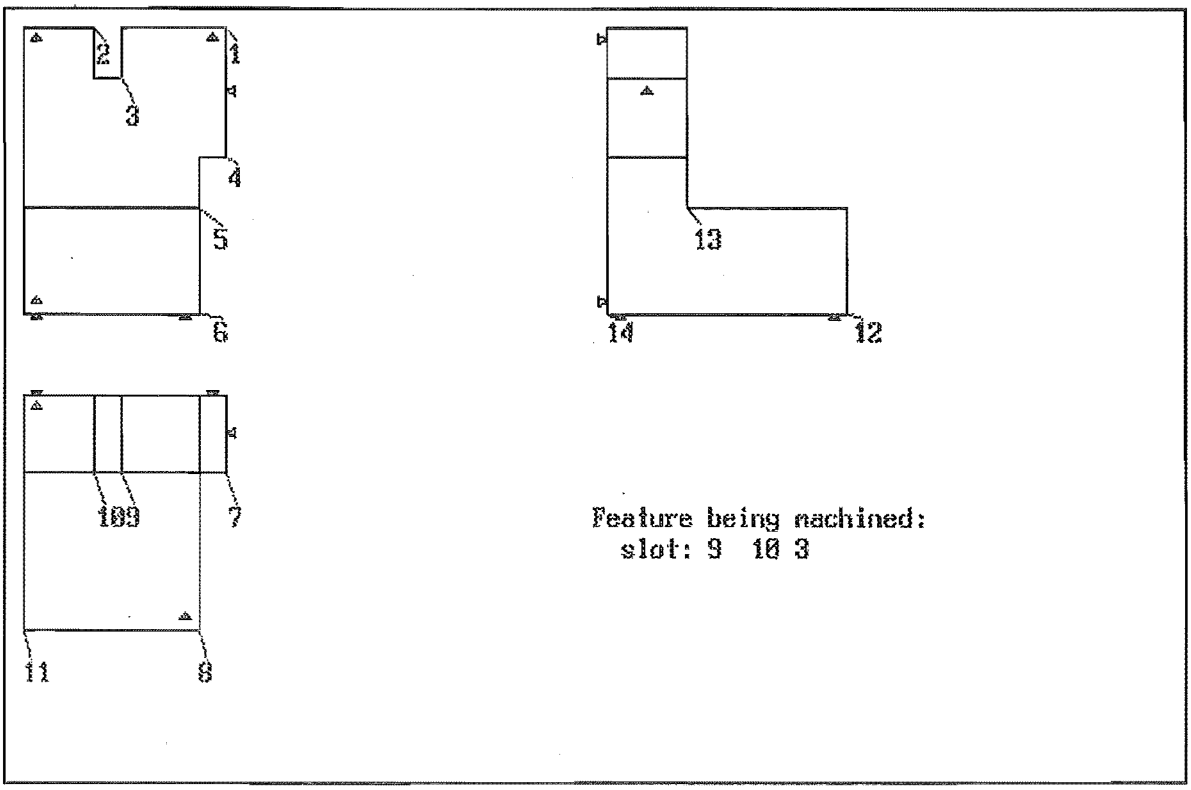


Fig.8.6: Process picture for cutting slot(9, 10, 3).

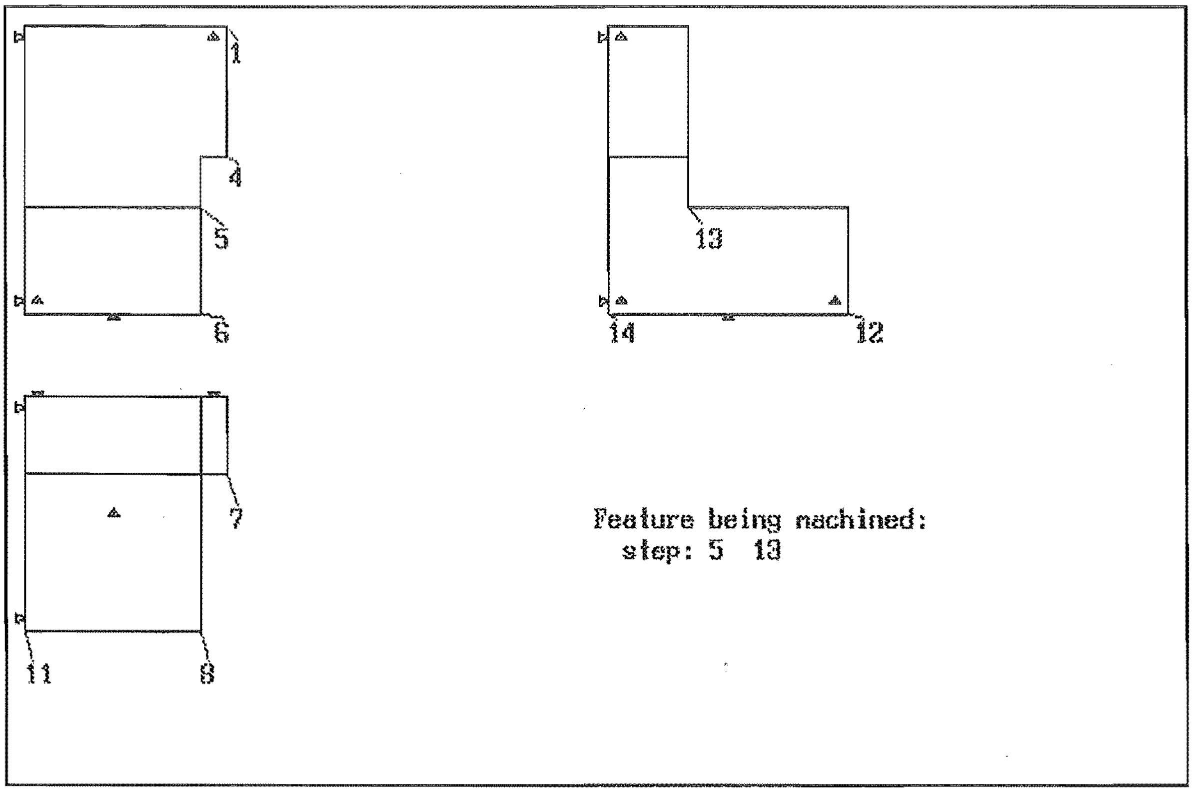


Fig.8.7: Process picture for cutting step (5, 13).

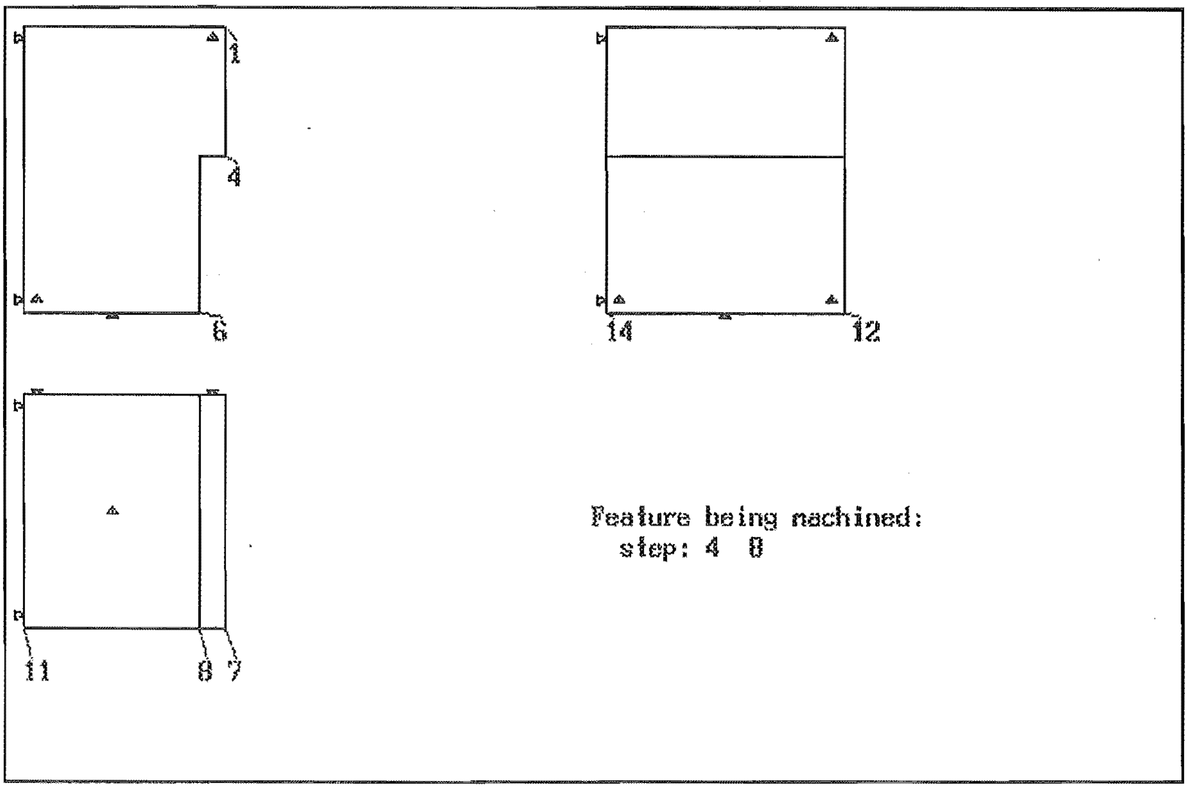


Fig.8.8: Process picture for cutting step (4, 8).

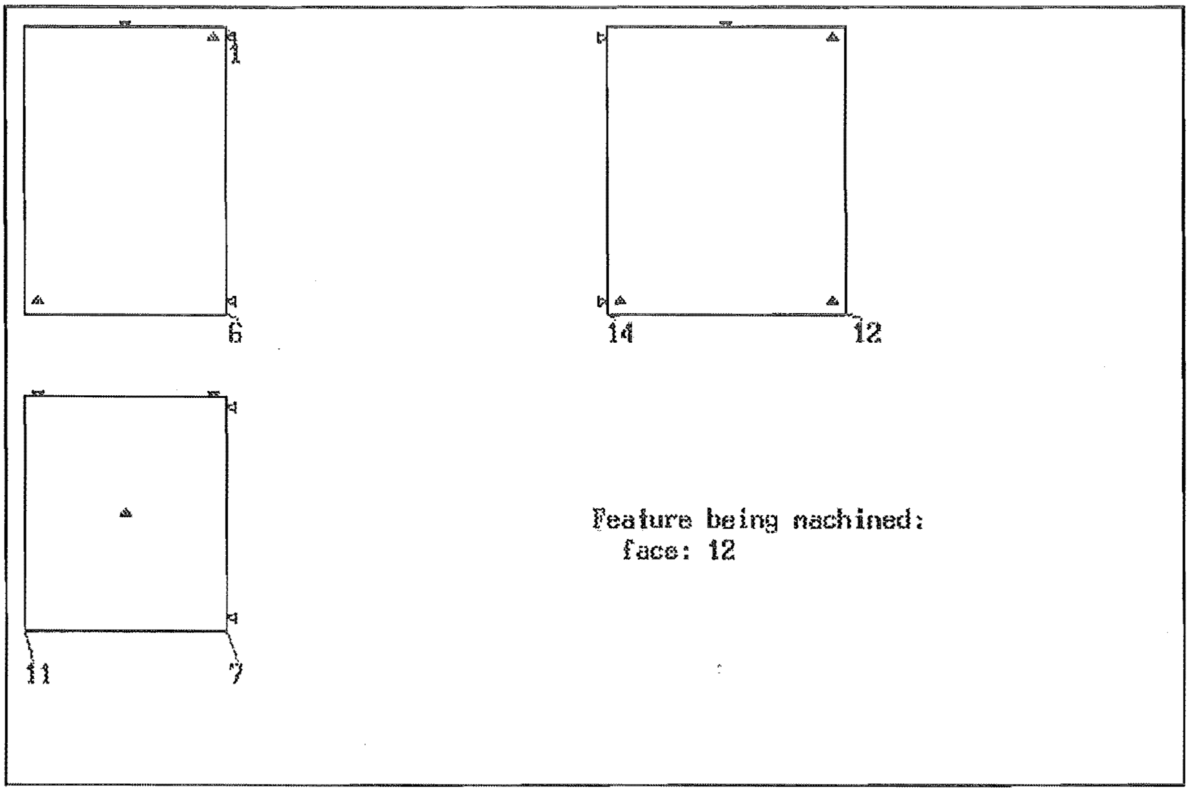


Fig.8.9: Process picture for cutting surface (12).

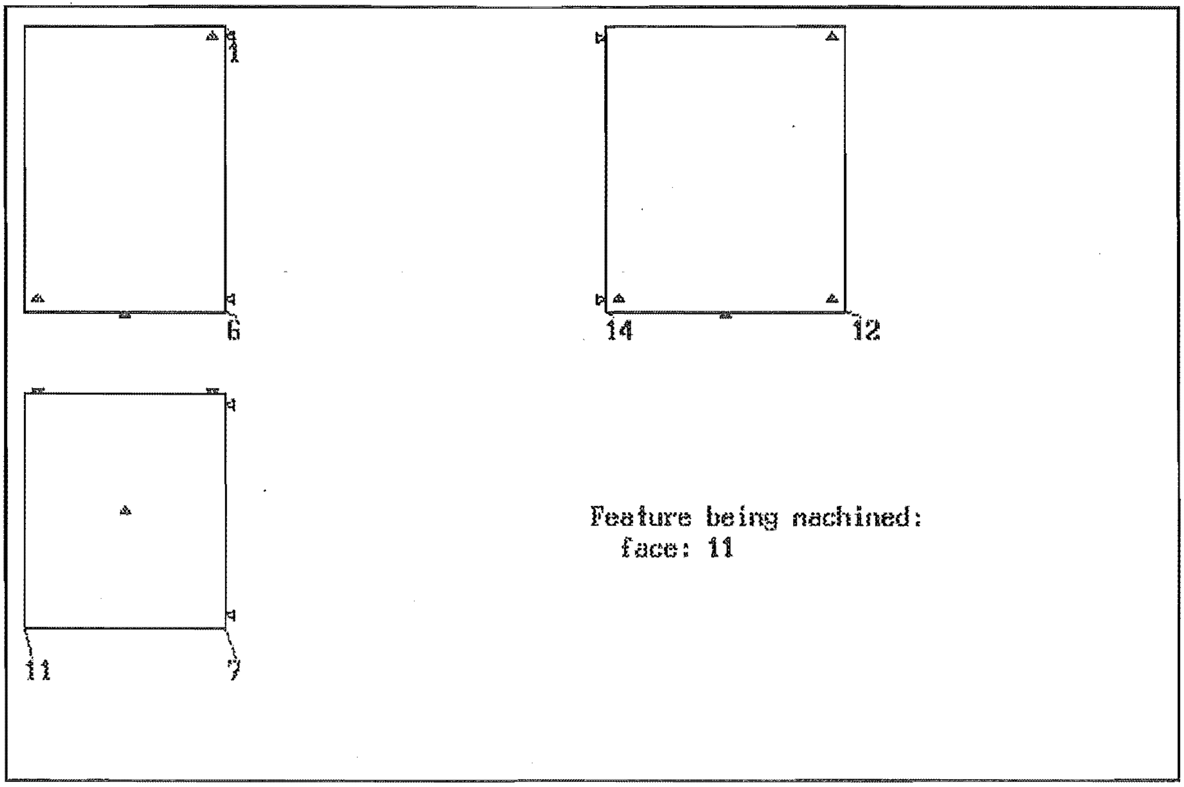


Fig.8.10: Process picture for cutting surface (11).

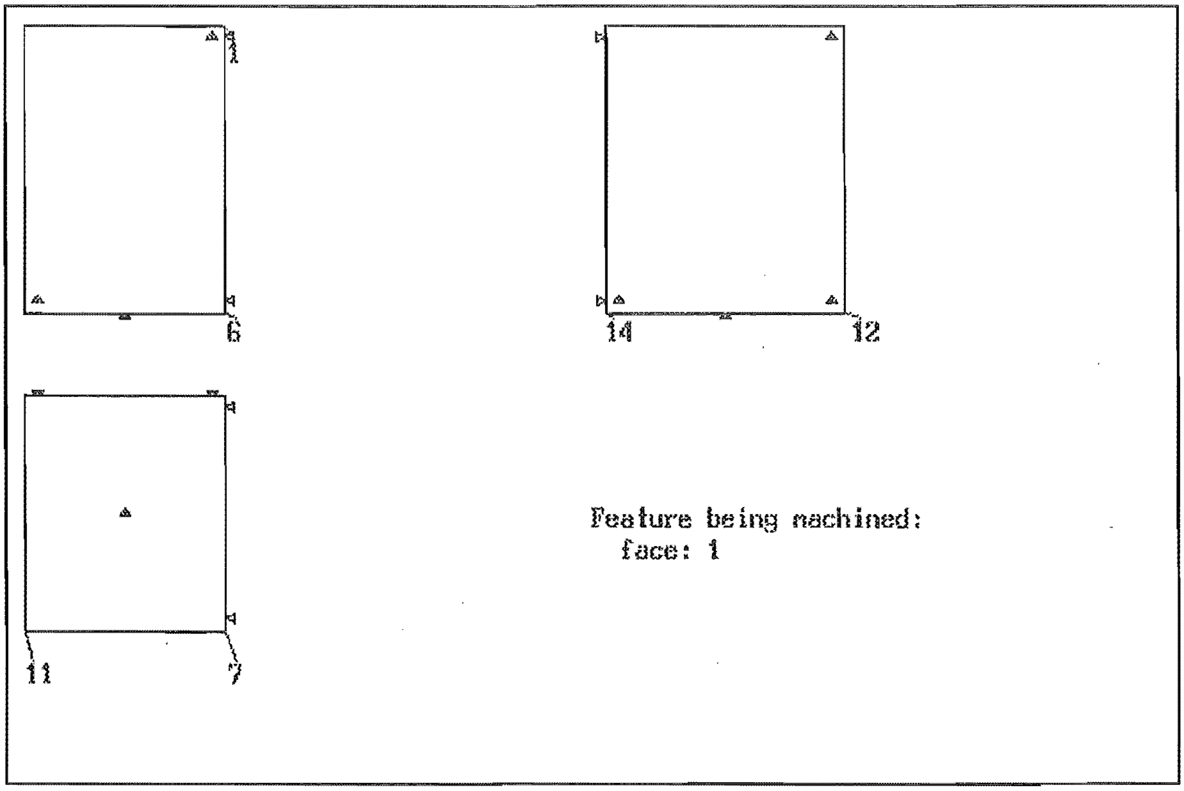


Fig.8.11: Process picture for cutting surface (1).

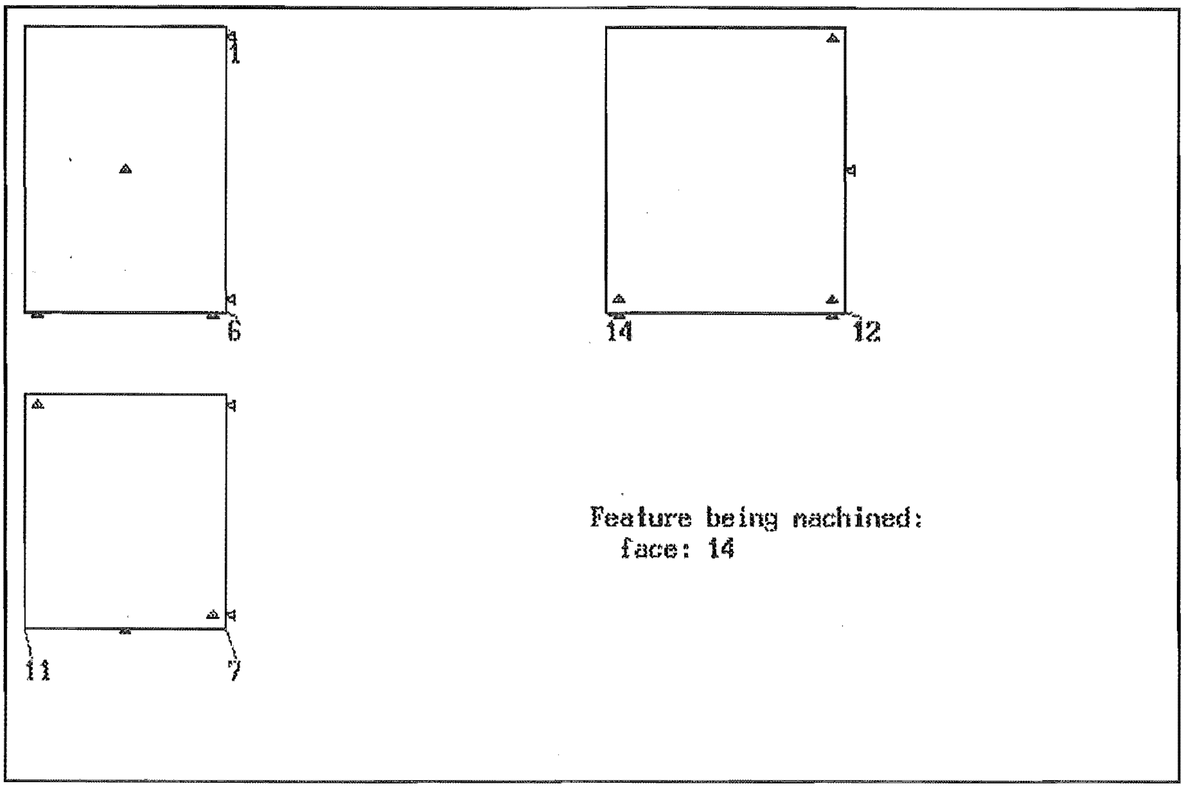


Fig.8.12: Process picture for cutting surface (14).

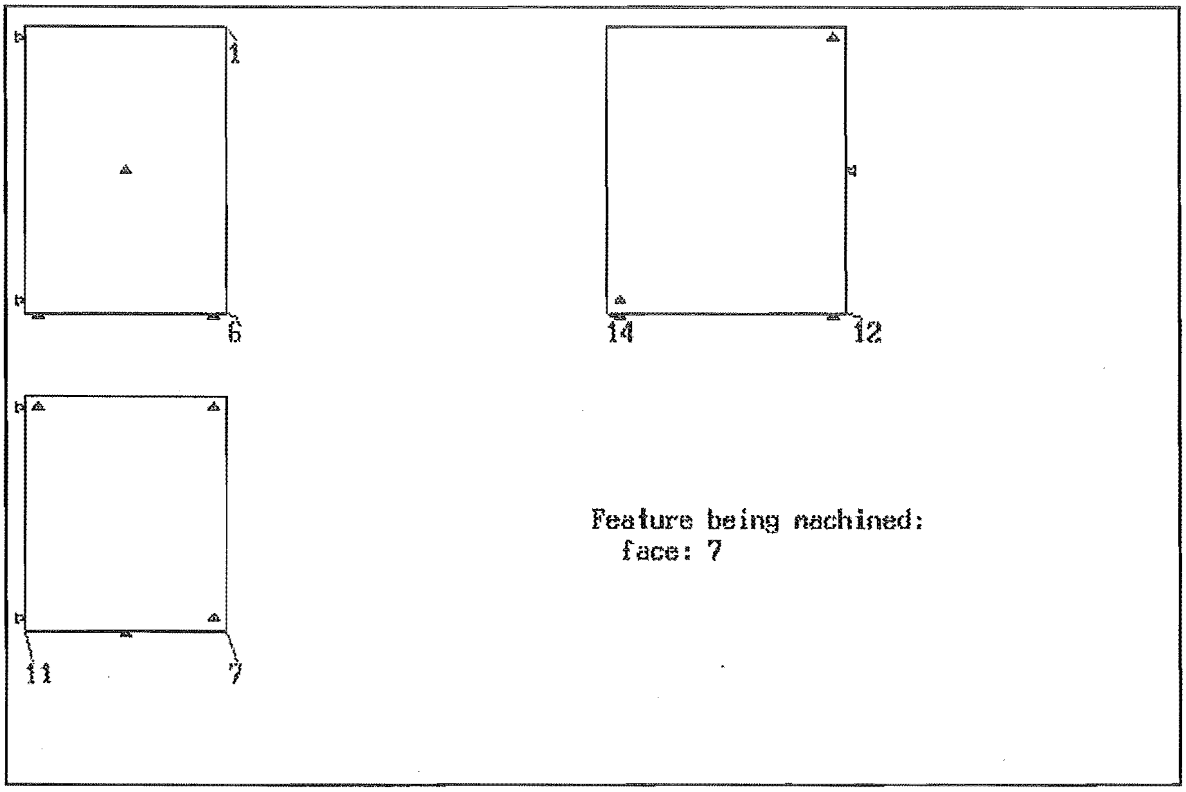


Fig.8.13: Process picture for cutting surface (7).

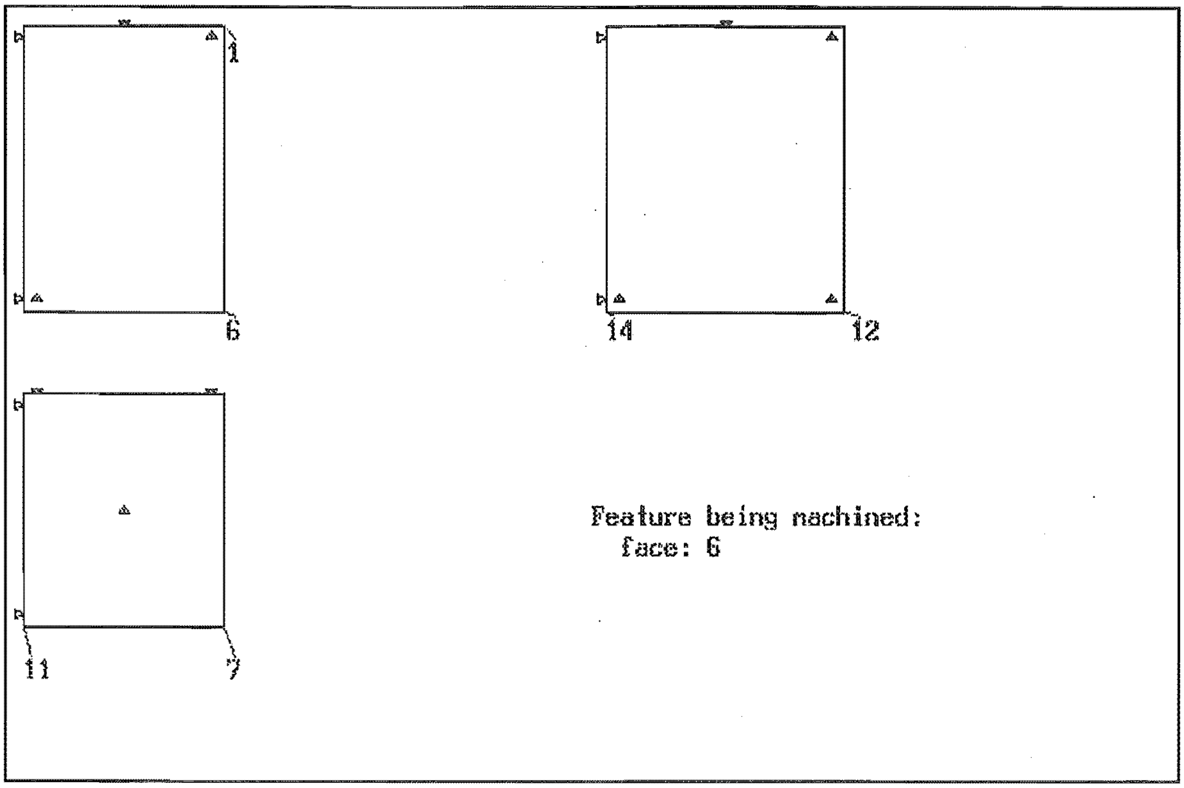
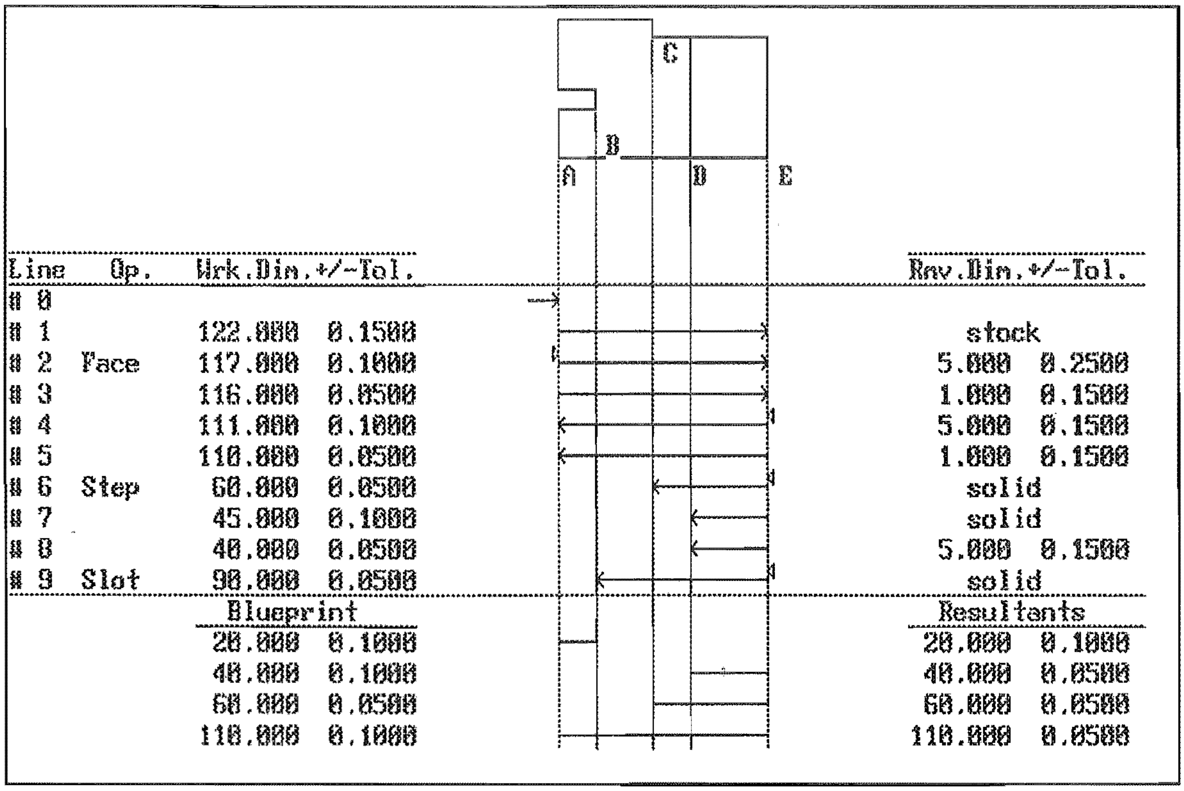


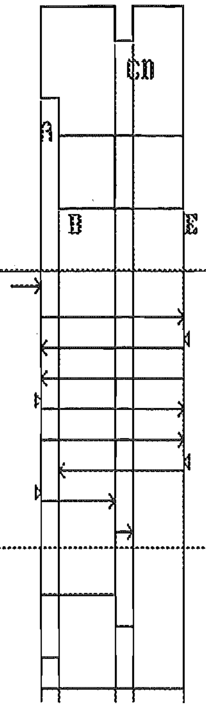
Fig.8.14: Process picture for cutting surface (6).



Line	Op.	Wrk.Dim.	+/-Tol.	Rev.Dim.	+/-Tol.
# 0					
# 1		122.000	0.1500	stock	
# 2	Face	117.000	0.1000	5.000	0.2500
# 3		116.000	0.0500	1.000	0.1500
# 4		111.000	0.1000	5.000	0.1500
# 5		110.000	0.0500	1.000	0.1500
# 6	Step	60.000	0.0500	solid	
# 7		45.000	0.1000	solid	
# 8		40.000	0.0500	5.000	0.1500
# 9	Slot	90.000	0.0500	solid	

Blueprint		Resultants	
20.000	0.1000	20.000	0.1000
40.000	0.1000	40.000	0.0500
60.000	0.0500	60.000	0.0500
110.000	0.1000	110.000	0.0500

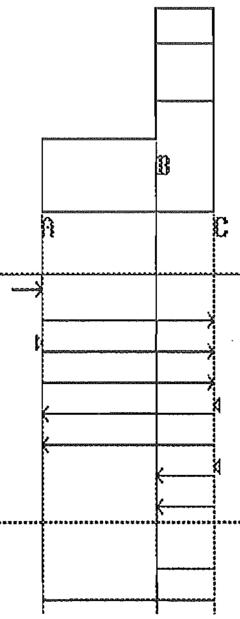
Fig.8.15: Tolerance chart # 1.



Line	Op.	Wrk.Dim.	+/-Tol.	Rav.Dim.	+/-Tol.
# 0					
# 1		87.000	0.1500	stock	
# 2	Face	82.000	0.1000	5.000	0.2500
# 3		81.000	0.0500	1.000	0.1500
# 4		76.000	0.1000	5.000	0.1500
# 5		75.000	0.0500	1.000	0.1500
# 6	Step	65.000	0.0500	solid	
# 7	Slot	39.000	0.0500	solid	
# 8		10.000	0.0500	solid	

Blueprint		Resultants	
39.000	0.1000	39.000	0.0500
10.000	0.0500	10.000	0.0500
10.000	0.1000	10.000	0.1000
75.000	0.1000	75.000	0.0500

Fig.8.16: Tolerance chart # 2.



Line	Op.	Wrk.Dim.	+/-Tol.	Rav.Dim.	+/-Tol.
# 0					
# 1		102.000	0.1500	stock	
# 2	Face	97.000	0.1000	5.000	0.2500
# 3		96.000	0.0500	1.000	0.1500
# 4		91.000	0.1000	5.000	0.1500
# 5		90.000	0.0500	1.000	0.1500
# 6	Step	35.000	0.1000	solid	
# 7		30.000	0.0500	5.000	0.1500

Blueprint		Resultants	
30.000	0.1000	30.000	0.0500
90.000	0.1000	90.000	0.0500

Fig.8.17: Tolerance chart # 3.

8.2 Example 2

The part for machining in this example is a casting (Fig.8.18). Fig.8.19 shows the drawing of the finished part. Only slotting and facing operations are required for this. The two slots are machined from solid cuts; that is the slots are not formed as part of the casting.

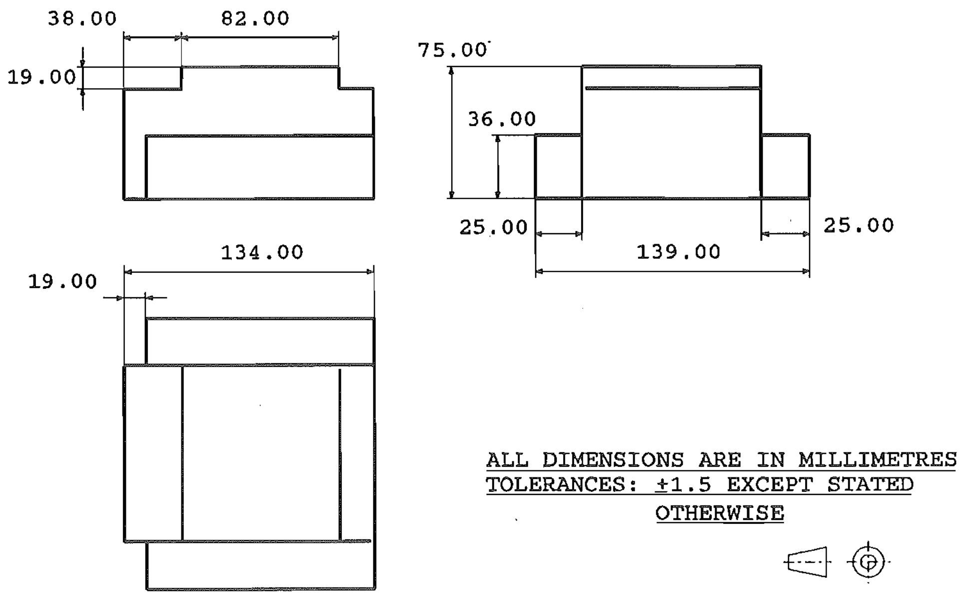


Fig.8.18: Drawing of a casting [76].

(1) Data files:

From the drawing of the finished part, the matrix spatial representation is developed. The production data are worked out from both drawings and a knowledge of the capability of the machine-tool.

Fig.8.20 shows how the principal axes are arranged on the part model.

Fig.8.21 shows the contents of the part model file.

Fig.8.22 shows the contents of the production data file.

The steps for starting up the system are the same as for Example 1.

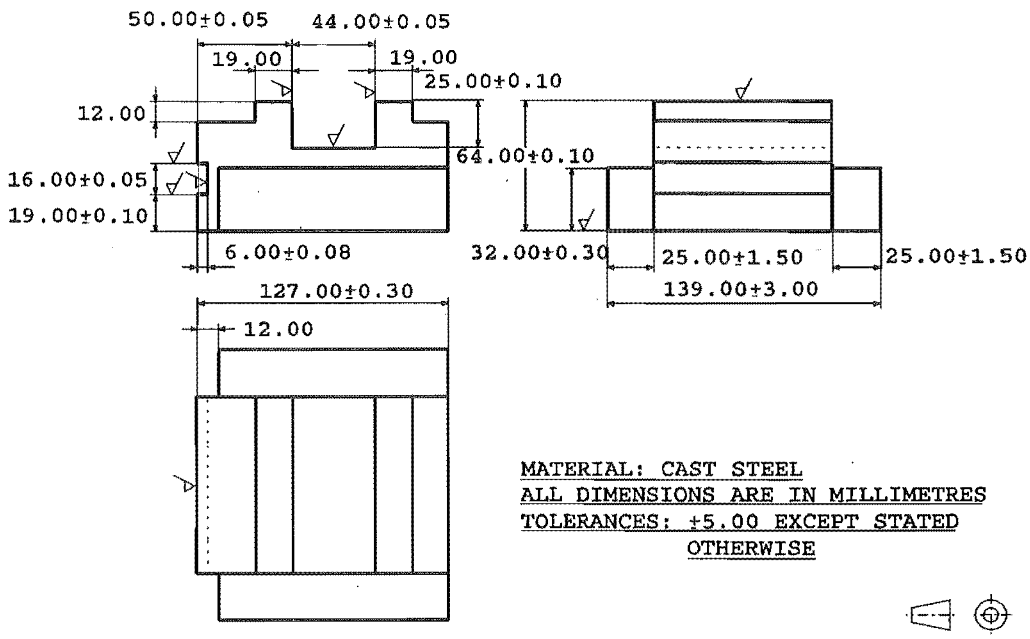


Fig.8.19: Drawing of the machined part.

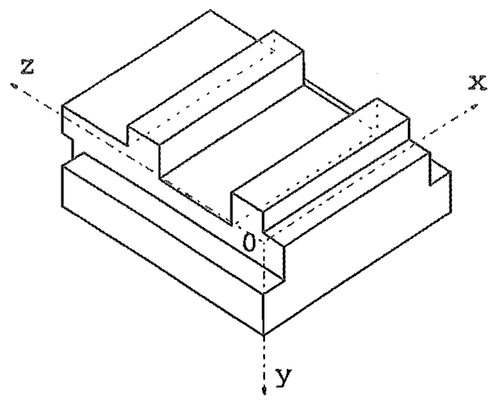


Fig.8.20: Part with x-y-z axes.

(2) Output of machining sequence:

Fig.8.23 shows the first screen display. Fig.8.24 to 8.28 are the results from the sequencing and locating routines. The summary of these results is given in Table 8.2.

(3) Output of the tolerance charts:

Fig.8.29 to 8.33 show the tolerance charts. Note that if a screen is not large enough to display the whole chart, another screen is used to display the remainder of the chart, and they are shown as different figures.

Table 8.2: Summary of machining sequence.

No.	Oper.	Cut and locating surface numbers			
		Cut	3-point	2-point	1-point
1	facing	10	7, 8	11	23
2	"	1	10	11	22
3	"	19	10	11	22
4	slotting	6, 9, 18	10	11	22
5	"	13, 14, 5	10	19, 20	22

8.3 Conclusion

The data for CAPPFD are of two types: one is concerned with the geometric model representation of the part, and the other, with the cutting conditions and the surfaces to be cut. The former is stored in a data file prior to execution of the program. The latter can either be interactively input into the system by the user or stored in a pre-prepared data file as for the first type. The output from the system consists of a set of process pictures showing the locating surfaces for all machining operations and a set of tolerance charts analysing all the dimensions of the part. These results can be used for tool designing purposes or as a basis for discussion with the product designer.

8 7 4

0.0	25.0	114.0	139.0
12.0	0.0	0.0	0.0
25.0	0.0	0.0	0.0
29.0	0.0	0.0	0.0
32.0	0.0	0.0	0.0
45.0	0.0	0.0	0.0
64.0	0.0	0.0	0.0

14.0	25.0	114.0	139.0
12.0	0.0	0.0	0.0
25.0	0.0	9.0	0.0
29.0	0.0	9.0	0.0
32.0	0.0	9.0	0.0
45.0	9.0	9.0	9.0
64.0	9.0	9.0	9.0

33.0	25.0	114.0	139.0
12.0	0.0	9.0	0.0
25.0	0.0	9.0	0.0
29.0	0.0	9.0	0.0
32.0	0.0	9.0	0.0
45.0	9.0	9.0	9.0
64.0	9.0	9.0	9.0

77.0	25.0	114.0	139.0
12.0	0.0	0.0	0.0
25.0	0.0	0.0	0.0
29.0	0.0	9.0	0.0
32.0	0.0	9.0	0.0
45.0	9.0	9.0	9.0
64.0	9.0	9.0	9.0

96.0	25.0	114.0	139.0
12.0	0.0	9.0	0.0
25.0	0.0	9.0	0.0
29.0	0.0	9.0	0.0
32.0	0.0	9.0	0.0
45.0	9.0	9.0	9.0
64.0	9.0	9.0	9.0

115.0	25.0	114.0	139.0
12.0	0.0	0.0	0.0
25.0	0.0	9.0	0.0
29.0	0.0	9.0	0.0
32.0	0.0	9.0	0.0
45.0	9.0	9.0	9.0
64.0	9.0	9.0	9.0

121.0	25.0	114.0	139.0
12.0	0.0	0.0	0.0
25.0	0.0	9.0	0.0
29.0	0.0	9.0	0.0
32.0	0.0	9.0	0.0
45.0	0.0	9.0	0.0
64.0	0.0	9.0	0.0

127.0	25.0	114.0	139.0
12.0	0.0	0.0	0.0
25.0	0.0	9.0	0.0
29.0	0.0	9.0	0.0
32.0	0.0	0.0	0.0
45.0	0.0	0.0	0.0
64.0	0.0	9.0	0.0

Fig.8.21: Part model representation.

```
10
2 1 10 19 11 15 15 23 21 24
4 10 8 16 20 20 12 24 22 21
1.5000  1.5000  1.5000  1.5000  1.5000
1.5000  1.5000  1.5000  1.5000  1.5000

16
2  9  6 2 18 16 11 14 13 14 12  8 1 23 21 21
10 10 9 4 19 19 20 19 14 15 13 10 5 24 24 22
64.000  19.000  16.000  12.000   6.000  12.000 127.000  50.000
44.000  19.000  19.000  32.000  25.000  25.000 139.000  25.000
0.1000  0.1000  0.0500  5.0000  0.0800  5.0000  0.3000  0.0500
0.0500  5.0000  5.0000  0.3000  0.1000  1.5000  3.0000  1.5000

3
2 1 2
2
 5.000  2.000
 0.100  0.050
2 19 20
2
 5.000  2.000
 0.100  0.050
1 10
1
 4.000
 0.050

0

2
3 6 9 18
2 19 20
2
 0.000  2.000
 0.000  2.000
 0.080  0.050
0
3 13 14 5
2 1 2
2
 0.000  5.000
 0.000  2.000
 0.100  0.050
0
```

Fig.8.22: Contents of production data file.

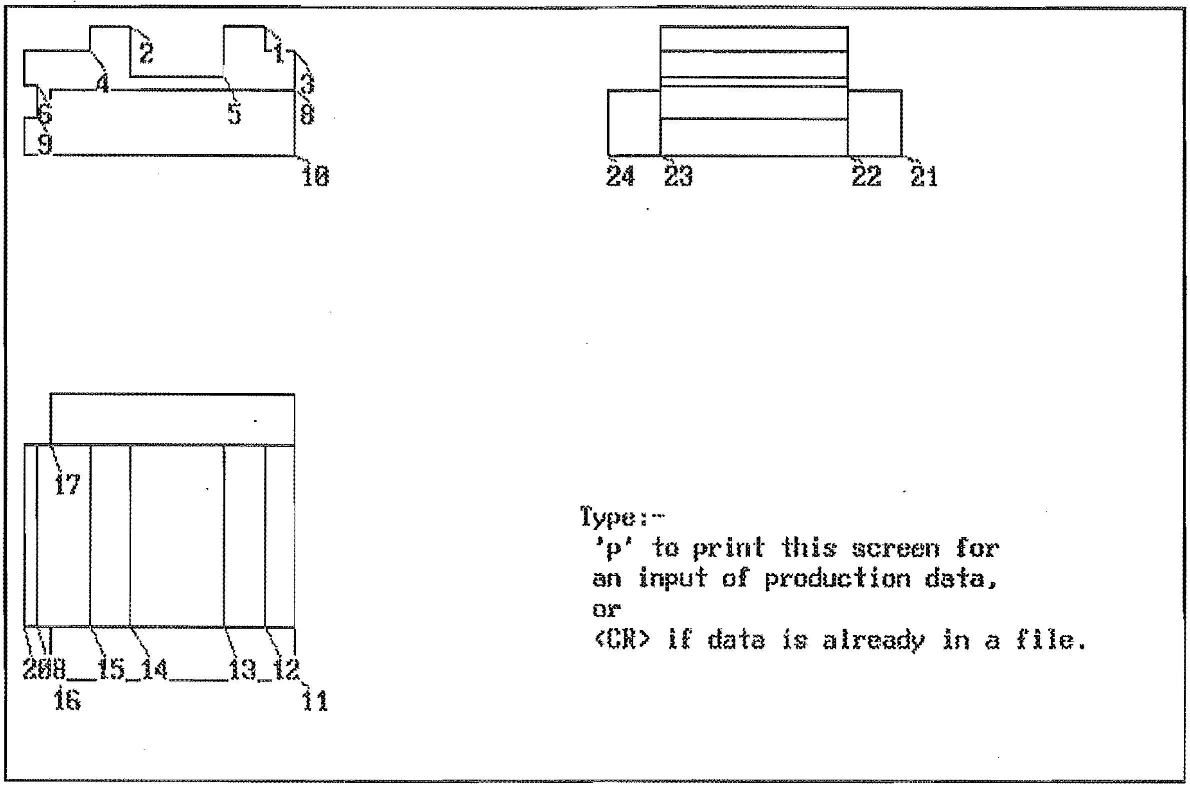


Fig.8.23: The first screen display.

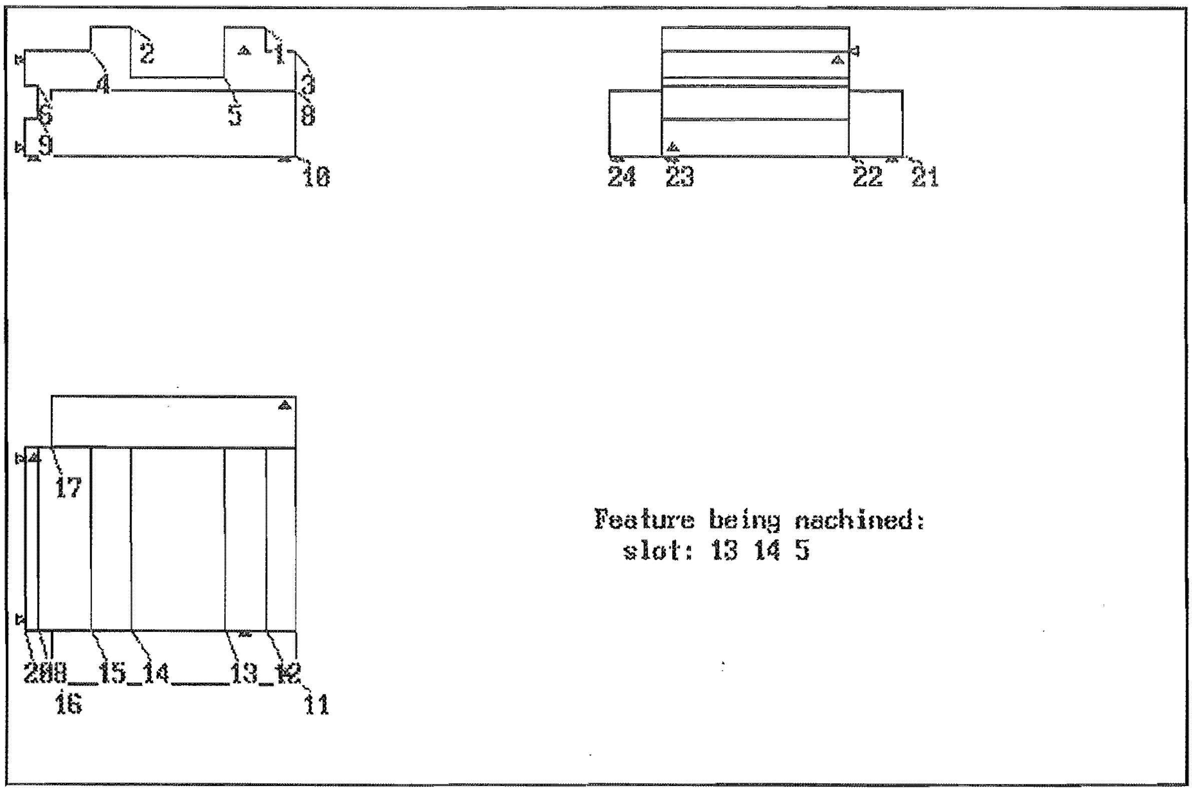


Fig.8.24: Process picture for cutting slot (13, 14, 5).

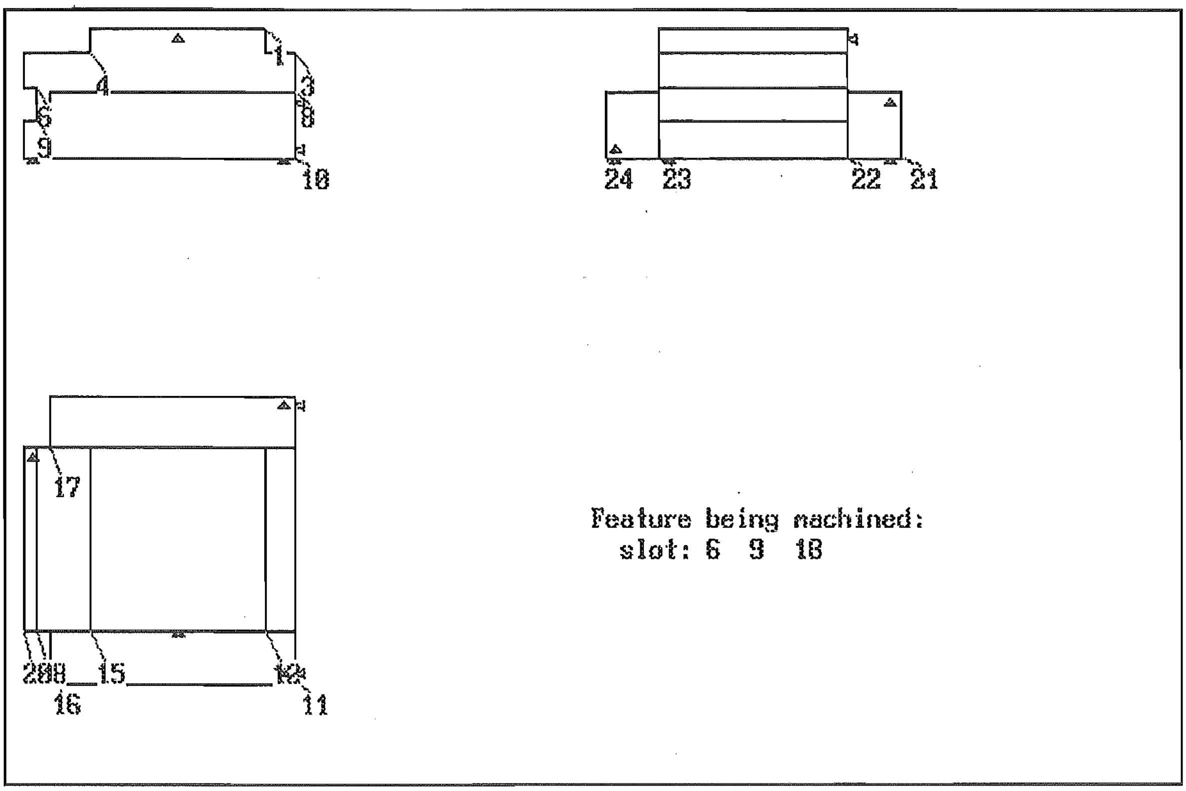


Fig.8.25: Process picture for cutting slot (6, 9, 18).

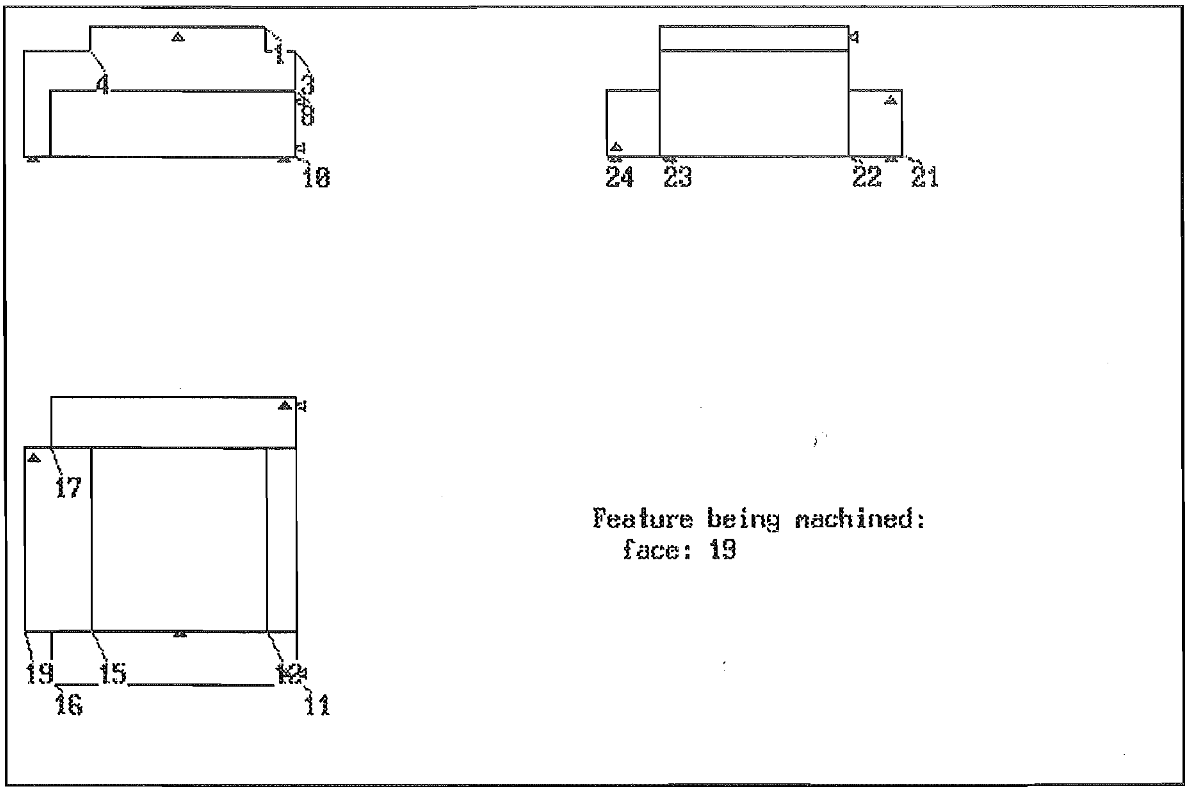


Fig.8.26: Process picture for cutting surface (19).

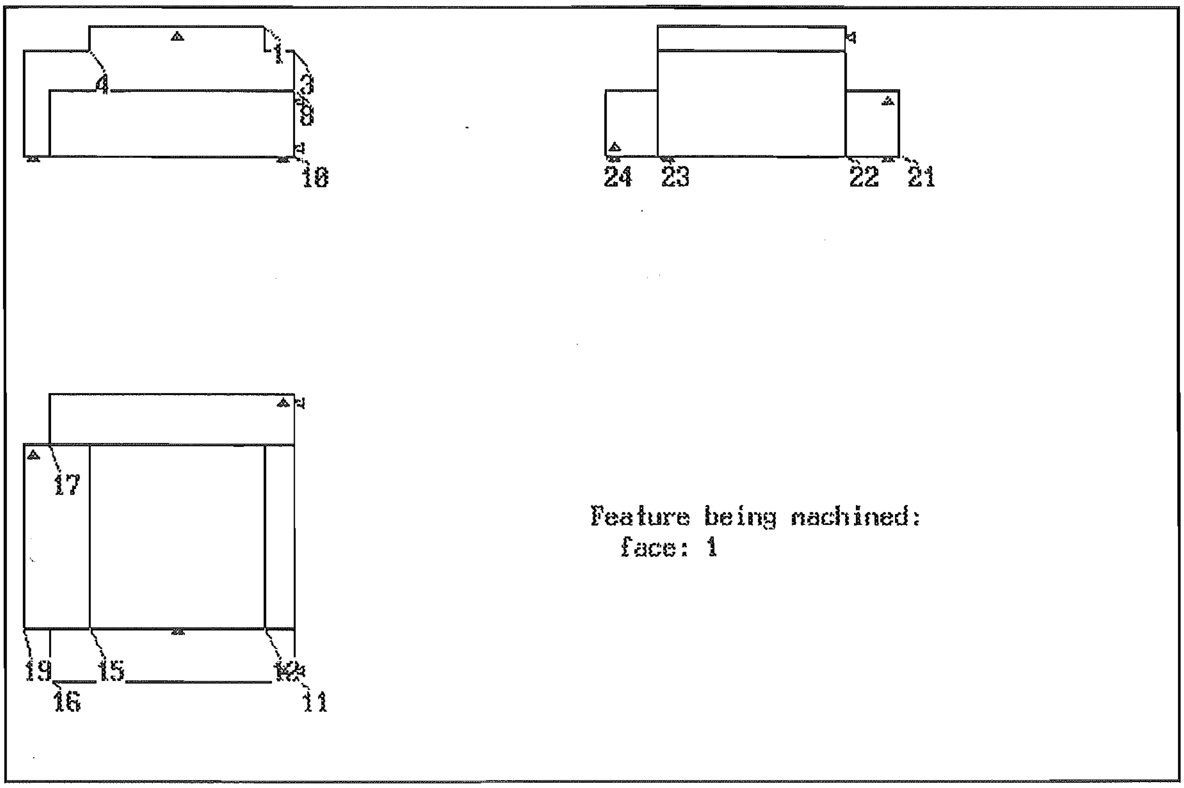


Fig.8.27: Process picture for cutting surface (1).

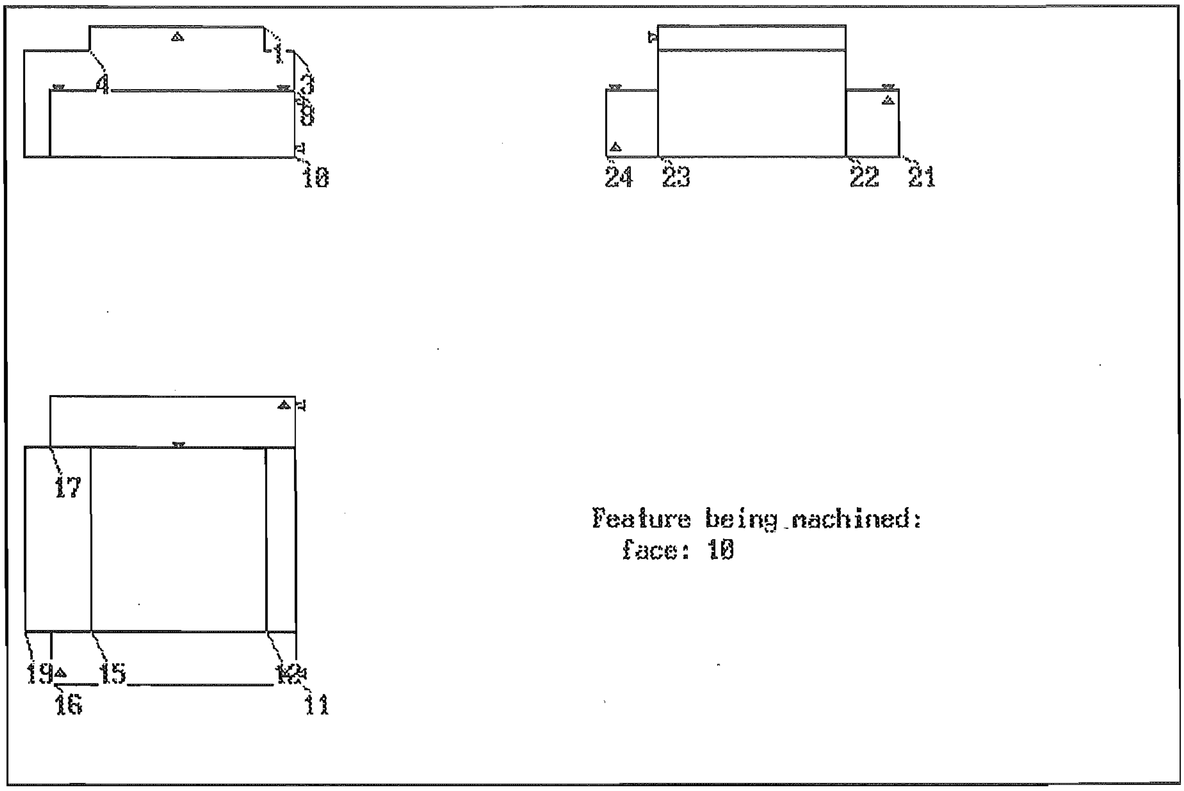
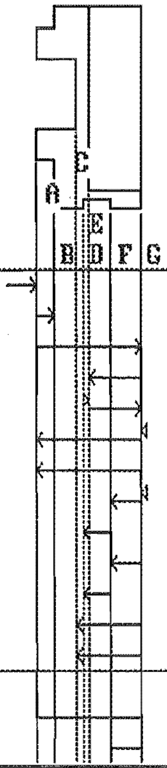
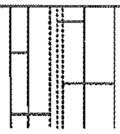


Fig.8.28: Process picture for cutting surface (10).



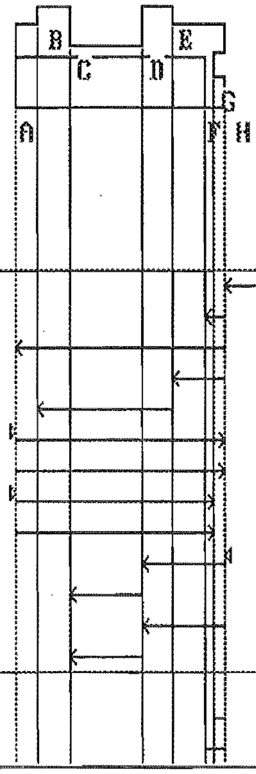
Line	Op.	Wrk.Dim.+/-Tol.		Rmv.Dim.+/-Tol.	
# 0					
# 1		19.000	1.5000	stock	
# 2		75.000	1.5000	stock	
# 3		36.000	1.5000	stock	
# 4	Face	32.000	0.0500	4.000	1.5500
# 5		66.000	0.1000	5.000	3.1500
# 6		64.000	0.0500	2.000	0.1500
# 7	Slot	21.000	0.0000	solid	
# 8		12.000	0.0800	solid	
# 9		19.000	0.0500	2.000	0.1300
#10		16.000	0.0500	2.000	0.2600
#11		44.000	0.1000	solid	
#12		39.000	0.0500	5.000	0.1500
		Blueprint		**Resultants**	
		64.000	0.1000	64.000	0.0500
		19.000	0.1000	19.000	0.0500

Fig.8.29: Tolerance chart # 1.



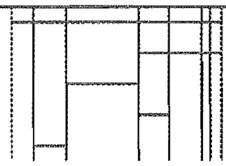
16.000	0.0500	16.000	0.0500
12.000	5.0000	12.000	4.6000
32.000	0.3000	32.000	0.0500
25.000	0.1000	25.000	0.1000

Fig.8.30: Tolerance chart # 1 (cont.)



Line	Op.	Wrk.Dim.	+/-Tol.	Rsv.Dim.	+/-Tol.
# 0					
# 1		19.000	1.5000	stock	
# 2		134.000	1.5000	stock	
# 3		38.000	1.5000	stock	
# 4		82.000	1.5000	stock	
# 5	Face	129.000	0.1000	5.000	1.6000
# 6		127.000	0.0500	2.000	0.1500
# 7	Slot	123.000	0.0000	solid	
# 8		121.000	0.0500	2.000	0.1300
# 9		52.000	0.1000	solid	
#10		48.000	0.1000	solid	
#11		50.000	0.0500	2.000	0.1500
#12		44.000	0.0500	2.000	0.3000
		Blueprint		Resultants	
		6.000	0.0000	6.000	0.1000
		12.000	5.0000	12.000	3.0500

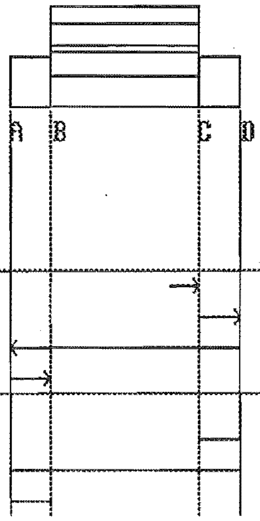
Fig.8.31: Tolerance chart # 2.



127.000	0.3000	127.000	0.0500
50.000	0.0500	50.000	0.0500
44.000	0.0500	44.000	0.0500
19.000	5.0000	19.000	3.1000
19.000	5.0000	19.000	4.6500

Fig.8.32: Tolerance chart # 2 (cont.)

Line	Op.	Wrk.Dim.+/-Tol.		Rnv.Dim.+/-Tol.
# 0				
# 1		25.000	1.5000	stock
# 2		139.000	1.5000	stock
# 3		25.000	1.5000	stock



Blueprint		Resultants	
25.000	1.5000	25.000	1.5000
139.000	3.0000	139.000	1.5000
25.000	1.5000	25.000	1.5000

Fig.8.33: Tolerance chart # 3.

9. CONCLUSIONS AND RECOMMENDATIONS

This report puts forwards a new concept of computer-aided process planning. Although the concept is commonly applied in manual process planning, it has been neglected by the designers of most of the CAPP systems. The CAPPFD system also incorporates a tolerance charting routine to check the feasibility of the proposed processing sequence. This feature has not previously been available in CAPP systems for prismatic parts. However, only a start has been made, to prove the feasibility of incorporating these techniques, and there is still a lot of work to be done to produce a fully developed system. This is left for future research.

9.1 Conclusions

In generating the machining sequence, CAPPFD ensures dimensional and geometric control over the workpiece. It demonstrates that it is feasible to use the dimensional relationships as a basis for machining sequence planning, and for locating the workpiece. Therefore, the general aim of this research project has been achieved.

The logic for sequencing and locating the workpiece developed in CAPPFD, can be adopted by other CAPP systems when the solid modeller is fully developed.

With regards to the tolerance charting technique, CAPPFD has introduced a new method for tolerance stack calculations. This method may be used in manual or computerised charting.

9.2 Recommendations for future research

CAPPFD uses a spatial representation technique to model the machined part in the computer. It is a simple method for solid modelling, and it can represent the part geometry accurately only those containing the edges parallel to the x, y or z axis. As a result, the system is confined to only 3 types of milling operation: facing, step cutting and slotting, which restricts the system.

The system also has a limited capability for handling combined features, particularly, when a step is on another step. When an error due to this limitation occurs, the stock dimensions in the tolerance charts will not agree with the actual dimensions. However, this can be picked up quickly by the user, and changes can be made by modifying the depths of cut to be consistent with the sequence. These shortcomings and others are subject for future research. Some aspects of the future research are listed below:

(1) **Other machined features:** Features such as holes, closed and open pockets should be included in the system. This could be done by using an extended part model representation. It is suggested that the sequence in which the new features are to be processed must be pre-planned: in the same way as facing before step cutting, step cutting before slotting in the present work. The priority given will depend on the type of part family and on the practical limitations in machining the features.

(2) **Heat-treatment:** Surface grinding normally follows case hardening. At present, the tolerance chart module cannot handle the case depth resulting from a grinding process. So these two operations are not included in the system. With

further development of the tolerance chart technique, these operations could be readily incorporated

(3) **Tolerance chart calculations:** Because the technique developed for calculating the tolerance stacks is simple and suitable for programming, it should be further developed to chart other machined as well as non-machined features such as tapers, radial surfaces, and hardened-case depth.

(4) **Machining tolerance generation:** An expert system could be developed for generating the machining tolerances of the prosessing operations involved. Some work, based on the standard International Tolerance (IT) grades of average machine-tool condition [33, 71], was done in this area, but it does not take into account the skill and experience of the machinist. This is the area where the expert system approach should be applied.

(5) **Mechanical control:** An expert system should be developed for designing a physical system. This may involve the use of other engineering analysis package, such as the program for finite element analysis; the data base of fixturing elements; and the application program for designing a fixture, such as Ngoi's system [52].

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APPENDIX A

GRAPH-THEORETIC APPROACH TO TOLERANCE CHARTING

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A major problem for manufacturing companies is the effective integration of design and production. Tolerance charts provide one means of aiding this integration. Manually produced charts are time-consuming and have not been widely adopted. This paper presents an elegant graph-theoretic approach to tolerance charting suitable for use with a microcomputer. The approach has the potential to significantly reduce the amount of work required in charting, and so it can be used by small companies as well as large ones.

Key words: Graph theory; Tolerance charts

1. Introduction

A tolerance chart is a graphical representation of a sequence of machining operations on a workpiece. It shows the machined dimensions, the tolerance and the amount of stock to be removed at each step in the sequence. The main use of a tolerance chart is as a process planning tool to ensure that a specific processing sequence is appropriate for producing a product of the required finished dimensions, and that there is adequate metal to be removed at each machining operation. It also provides an easy understood means for communication between the process planner and the designer. The chart can disclose any problems concerned with tolerance control on the workpiece before machining occurs, so that they can be analysed and the appropriate remedial action taken.

Although the tolerance chart has been used for controlling dimensions of machined parts since the early 1950s, the technique is practised only within certain industries, for example the aircraft industry [1] and the automobile industry [2]. The reluctance to accept the method comes from the complexity of the chart itself: time and effort are required to learn and to practise the technique. This obstacle has led to various methods being proposed to simplify the charting. Among the well-known methods are those proposed by Johnson [3], Mooney [4], Wade [5], and Gadzala [6]. Even with these methods, however, the task is still time-consuming and error-prone.

It was not until 1982 that Sack [7] reported the use of the tolerance chart in an automatic process planning system. This report opened up a new and efficient way of computerised tolerance charting. Then Ahluwalia and Karolin [8] used a minicomputer with a graphics routine to generate the tolerance chart. Recently, Xiaoqing and Davies [9] have developed a computer package for tolerance charting based on a matrix-tree-chain method. These programs are limited to a minicomputer or mainframe computer; there has not yet been any report of a similar application being developed for use on a microcomputer.

The intention of this paper is to describe another tolerance-charting approach, based on graph theory, which is appropriate for microcomputer application. The approach is described by means of an example of a simple tolerance chart in which a chosen sequence of machining operations cannot meet the designer's specifications. The example is worked out manually and then the computer output for the particular example is presented.

2. Development of the Technique

The technique of tolerance charting developed here is based on the "rooted-tree" method, which is a special kind of directed graph as described by Robinson and Foulds [10]. The tolerance in Fig. 2 prepared for the workpiece shown in Fig. 1, will be used as an example to illustrate the basic ideas of the technique. This chart is slightly different from those of Johnson [3], Wade [5] and Gadzala [6], in that no intermediate balance dimension is shown between the working dimensions.

All the workpiece surfaces are identified by capital letters. The surface pointed to by the arrowhead is the machined faced, and the surface identified by a dot surrounded by a circle is the locating face. Since the tolerance is concerned only with length dimensions, all diameter dimensions are omitted from the chart. (It should also be noted that operation 20 is not listed in the chart because this operation does not have any effect on the finished dimensions.)

The most important use of the chart is for finding the route from a cut face to the original surface. Two approaches to the solution will be presented: a diagram and a tabulation method. Either approach can solve the problem, but the diagram is more convenient for manual working and makes the algorithm easier to understand.

Considering Fig. 2, the essence of this example can be stated as follows:

Operation 10: face A of the stock is defined relative to locating surface D

Operation 30: face B is defined relative to surface D

Operation 40: face A1 is defined relative to surface D (the numeric suffix is

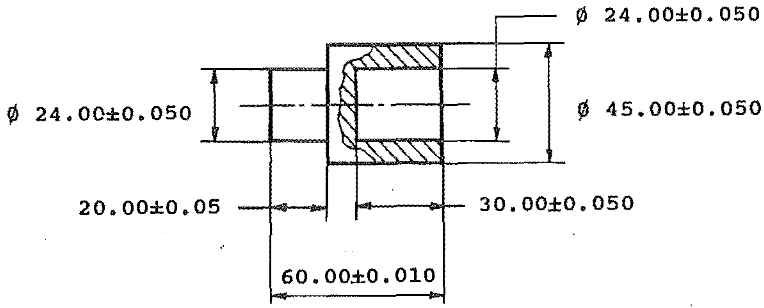
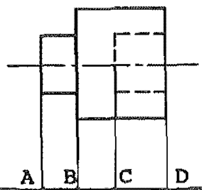


Fig.1. Workpiece dimensions (in millimetres).



Line no.	Op.no.	Face	M/C	working dim. basic	working dim. ±tol.	stock removal basic	stock removal ±tol.
0							
1	10	A	saw	61.20	0.200		
2	30	B	lathe	40.60	0.025	20.60	solid
3	40	A1	lathe	60.70	0.025	0.50	0.225
4	50	D1	lathe	60.20	0.025	0.50	0.050
5	60	C	drill	30.60	0.025	29.60	solid
6	70	C1	lathe	30.10	0.025	0.50	0.050
7	80	A2	grind	60.10	0.005	0.10	0.030
8	90	D2	grind	60.00	0.005	0.10	0.010

blueprint		resultant	
20.00	0.050	20.00	0.080
30.00	0.050	30.00	0.060
60.00	0.010	60.00	0.005

Fig.2. Tolerance chart for the workpiece in Fig.1.

necessary to distinguish between the old and the newly machined surfaces)

Operation 50: face D1 is defined relative to surface A1

Operation 60: face C is defined relative to surface A1

Operation 70: face C1 is defined relative to surface A1

Operation 80: face A2 is defined relative to surface D1

Operation 90: face D2 is defined relative to surface A2

This is summarized in Table 1 (which later becomes the first three columns of Table 2 in the tabulation approach). Diagrammatically, the machining sequence can be represented by a "rooted-tree" graph, with the original locating surface D (the "root") at the top, as shown in Fig. 3. In Fig. 3, each link represents a machining operation with its associated working dimension, and each node represents a machined and/or a locating surface; some nodes are both a machined and a locating surface. The path from any one node of the tree to another can be easily picked out by inspection. The links in a path define the machining operations, and determine the dimensions, relevant to the two surface nodes. The distance, basic dimension and tolerance between the two surfaces are the result of all machining operations that are the links in the path. For example, the path from C1 to A2 is C1 A1 D1 A2. The tolerance of the distance between C1 and A2 is equal to the sum of the tolerances of the machining operations in the path.

Table 1. Machined faces and locating surfaces.

Operation	Machined face	Locating face
10	A	D
30	B	D
40	A1	D
50	D1	A1
60	C	A1
70	C1	A1
80	A2	D1
90	D2	A2

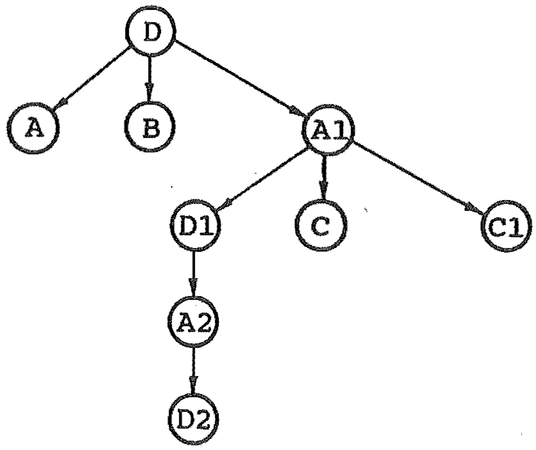


Fig.3. Rooted-tree diagram.

In the tabulation method, the paths in the rooted tree are summarized as shown in Table 2. Under the "path" heading in the table, the path from the new surface node to the root is listed. This is constructed by adding the new face to the corresponding locating surface and the path from the locating surface to the root, which has already been computed. In the "reversed path" column, the path elements are reversed.

To find the path from any node X to any node Y, the two reversed paths are compared and the last node Z at which they agree is identified. The path from X to Y is then given by the path from X to Z ("path X") followed by the path from Z to Y ("reversed path Y"). For example:

1. Find the path from C1 to A2.

   Reversed paths: C1 = D A1 C1

   A2 = D A1 D1 A2

   Z = A1; hence the path from C1 to A2 is C1 A1 D1 A2.

2. Find the path from A1 to A2.

   Reversed paths: A1 = D A1

   A2 = D A1 D1 A2

Z = A1; hence the path is A1 D1 A2 (X occurs in the reversed path of Y).

The links in a path are needed to find the tolerances. These links are identified and listed against the machined surface at the end of the path, so that they can be immediately extracted to add their tolerances together.

Table 2. Paths in rooted-tree diagram.

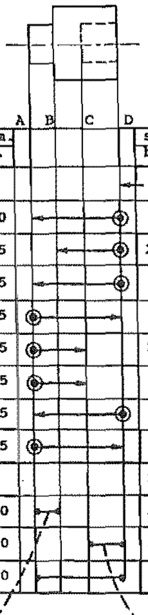
Operation	New face	Locating face	Path	Reversed path
10	A	D	A D	D A
30	B	D	B D	D B
40	A1	D	A1 D	D A1
50	D1	A1	D1 A1 D	D A1 D1
60	C	A1	C A1 D	D A1 C
70	C1	A1	C1 A1 D	D A1 C1
80	A2	D1	A2 D1 A1 D	D A1 D1 A2
90	D2	A2	D2 A2 D1 A1 D	D A1 D1 A2 D2

3. Applications

Fig. 4 summarises the procedure outlined above. First the basic data must be prepared. This data includes the processing sequence, the tolerances for all machining operations and the minimum amount of metal to be removed at each machining cut. First a sketch of the workpiece, and then lines and letters identifying all surfaces to be processed, are entered in the tolerance chart. After this is done, the basic data and the charting symbols are entered in the appropriate columns. At this stage, columns 5, 8 and the "resultant" column are empty. These columns will contain the values that are to be calculated.

Parts (b) and (e) of Fig. 4 are not parts of the tolerance chart; they are shown to clarify the calculations. The table in Fig. 4(b) is similar to Table 2, except that two new columns have been added: column 13 records the links in a path required for calculating a balance dimension, and column 14 is for the line numbers corresponding to those links in column 13.

(a)



1 Line no.	2 Op.no.	3 Face	4 M/C	5 working dim. basic	6 ±tol.	7 stock removal basic	8 ±tol.
0							
1	10	A	saw	61.20	0.200		
2	30	B	lathe	40.60	0.025	20.60	solid
3	40	A1	lathe	60.70	0.025	0.50	0.225
4	50	D1	lathe	60.20	0.025	0.50	0.050
5	60	C	drill	30.60	0.025	29.60	solid
6	70	C1	lathe	30.10	0.025	0.50	0.050
7	80	A2	grind	60.10	0.005	0.10	0.030
8	90	D2	grind	60.00	0.005	0.10	0.010
				blueprint		resultant	
				20.00	0.050	20.00	0.080
				30.00	0.050	30.00	0.060
				60.00	0.010	60.00	0.005

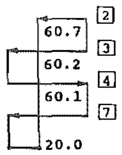
(b)

the sum of the tolerances of lines 1 and 3

9 cut face	10 loc. face	11 path	12 reversed path	13 link for a balance dim. link	14 line no.
D		D	D		
A	D	AD	DA		
B	D	BD	DB		
A1	D	A1D	DA1	AD	1
D1	A1	D1A1D	DA1D1	A1D	3
C	A1	CA1D	DA1C		
C1	A1	C1A1D	DA1C1	CA1	5
A2	D1	A2D1A1D	DA1D1A2	D1A1	4
D2	A2	D2A2D1A1D	DA1D1A2D2	A2D1	7
				A2D1,D1A1,A1D,BD	7,4,3,2
				C1A1,D1A1,A2D1,D2A2	6,4,7,8
				D2A2	8

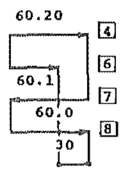
the sum of the tolerances of lines 2,3,4 and 7

(c)



working dim. of cut 2
= 60.7-(60.2-(60.1-20))
= 40.6 mm.

(d)



working dim. of cut 6
= 60.2 - (60.1-(60-30))
= 30.1 mm.

(e) 'rooted tree'

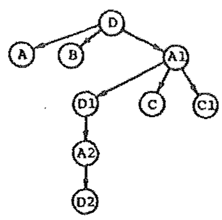


Fig.4. Summary of the method of tolerance charting. (All dimensions are given in millimetres; squares in parts (c) and (d) denote line numbers.)

To calculate the tolerance on the metal removal of a cut, in column 8, the tolerance of the cut is added to the sum of tolerances of the machining operations corresponding to the line numbers in column 14; for example, the tolerance of the metal removal in line 3 is

$$0.025 \text{ mm} + 0.200 \text{ mm} = 0.255 \text{ mm}$$

This method is also applied to calculate the tolerances of all the resultants.

The basic working dimensions are worked out from the bottom upwards in the following four ways, in the order of priority as listed:

1. Extract the basic working dimension from the basic blueprint dimensions; for example, the basic working dimension in line 8 is 60.00 mm.

2. Add or subtract the basic stock removal (column 7) to or from a known basic working dimension (column 5); for example, the basic working dimension in line 7 is

   basic working dimension in line 8 + 0.10 mm = 60.10 mm

   This rule applies when there is only one line number in column 14.

3. Calculate the unknown basic working dimension from the known working dimensions and a related drawing dimension; for example, the basic working dimension in line 2 is

   basic working dimension in line 3
   - {basic working dimension in line 4
   - (basic working dimension in line 7 - blueprint dimension)}

   Hence, the basic working dimension in line 2 is

   60.70 mm - {60.20 mm - (60.10 mm - 20.00)} = 40.60 mm

   This example is shown in Fig 4(c). Note that all line numbers involved in the calculation are in column 14 of the row corresponding to the basic drawing dimension of 20.00 mm.

4. Calculate the unknown basic working dimension from the known basic dimensions. Add or subtract the stock allowance to or from the working dimension, then apply rule 3. This method is used when a line of a working dimension has more than one line number in column 14. In this particular example, however, this case does not occur.

The same procedure as in rule 3 is used to calculate a basic resultant dimension, but in this case the unknown is the basic resultant instead of the basic working dimension.

By comparing the blueprint and the resultant tolerances in Fig 4(a), it can readily be seen that the chosen process sequence cannot produce a workpiece to the required specifications. This is because the tolerances of the resultant dimensions are greater than those of the corresponding blueprint dimensions. These differences signify that modifications should be made to either the type of machining operation, the tooling, or the machining sequence. Column 14 in Fig. 4(b) provides the line numbers of the working dimensions that relate to a finished product dimension. These line numbers can be used as a basis for such modifications.

4. Computer-Aided Tolerance Charting

A computer program for the microcomputer, based on the technique above, is being developed to chart the tolerances. Currently the program can analyse linear dimensional tolerances but not geometric tolerances. A typical output is shown in Fig. 5.

The program is one part of a complete process planning and fixture design package being developed at the University of Canterbury. The next stage of development is to interface the tolerance-chart program with a three-dimensional computer-aided design package to facilitate the analysis of dimensions and tolerances for all parts of a given product.

```
  line # 0:- metal removal:  0.000 +/- 0.000
  line # 1:- metal removal:  0.000 +/- 0.000
  line # 2:- metal removal:  20.600 +/- 0.000
  line # 3:- metal removal:  0.500 +/- 0.225
a line # 4:- metal removal:  0.500 +/- 0.050
  line # 5:- metal removal:  29.600 +/- 0.000
  line # 6:- metal removal:  0.500 +/- 0.050
  line # 7:- metal removal:  0.100 +/- 0.030
  line # 8:- metal removal:  0.100 +/-  0.01

  line # 0:- working dim.:  0.000 +/- 0.000
  line # 1:- working dim.:  61.200 +/- 0.200
  line # 2:- working dim.:  40.600 +/- 0.025
  line # 3:- working dim.:  60.700 +/- 0.025
b line # 4:- working dim.:  60.200 +/- 0.025
  line # 5:- working dim.:  30.600 +/- 0.025
  line # 6:- working dim.:  30.100 +/- 0.025
  line # 7:- working dim.:  60.100 +/- 0.005
  line # 8:- working dim.:  60.000 +/- 0.005

   from A to B  dwg. dim.= 20.000 +/- 0.050   resultant = 20.000 +/- 0.080
c  from C to D  dwg. dim.= 30.000 +/- 0.050   resultant = 30.000 +/- 0.060
   from A to D  dwg. dim.= 60.000 +/-  0.01   resultant = 60.000 +/- 0.005
```

Fig.5. The computer output: (a) basic stock removal dimensions and tolerances, (b) basic working dimensions and tolerances, (c) blueprint dimensions and resultant dimensions.

5. Concluding Remarks

The tolerance chart is one of the most useful tools for controlling workpiece dimensions during manufacture. The technique is not widely used in industry because it is complex, tedious and time-consuming. This paper has proposed a simple approach based on graph theory. The algorithm is easy to understand and to implement. It reduces the amount of work that is normally required when the chart is produced manually, and is particular suitable for use with a microcomputer. Thus tolerance charting is now feasible for small manufacturers.

In addition, the method can be easily incorporated into a generative process planning system to evaluate the feasibility of each process sequence generated. It therefore provides an important integrative link between design and production.

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APPENDIX B

Decision table technique

1. Decision tables

This appendix briefly describes decision tables. More details on the development and the use of these tables can be found in Ref.[77, 78, 79].

A decision table is a tabular display of the rules for decision making on a certain problem. Each rule in the table consists of 2 parts: the logical conditions and the action(s) to be taken according to the rule.

Fig.1 shows the 4 main sections of the decision table. They are:

condition stub	condition entry
action stub	action entry

Fig.1: Structure of decision table.

(1) The condition stub: This is a list of the questions or the conditions pertaining to a particular problem.

(2) The condition entry: The answers to the questions or the results from the tests of the conditions in the condition stub are shown in this part of the table. Each column is a combination of values for using a rule.

(3) The action stub: This section contains a list of all possible actions that should be taken.

(4) The action entry: This section specifies the action(s) to be taken according to a certain rule.

Table header | Rule header

DECISION TABLE	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*
direction of cut face	-1	-1	+1	+1	-1	-1	+1	+1
direction of locating face	-1	-1	+1	+1	+1	+1	-1	-1
position of locating face relative to cut face	* l>c	c>l	l>c	c>l	l>c	c>l	l>c	c>l
sign of the cut	-1	+1	+1	-1	-1	+1	+1	-1

Note: * l = locating face, c = cut face

Fig.2: Extended-entry table.

Rules

	1	*2*	*3*	*4*
condition stub	condition entry			
lo[c] > d1	0	0	1	1
lo[c] < d1	1	1	n	n
SIGN = +1	1	0	1	0
action stub	action entry			
ADD	X			X
SUBTRACT		X	X	

Fig.3: Limited-entry table.

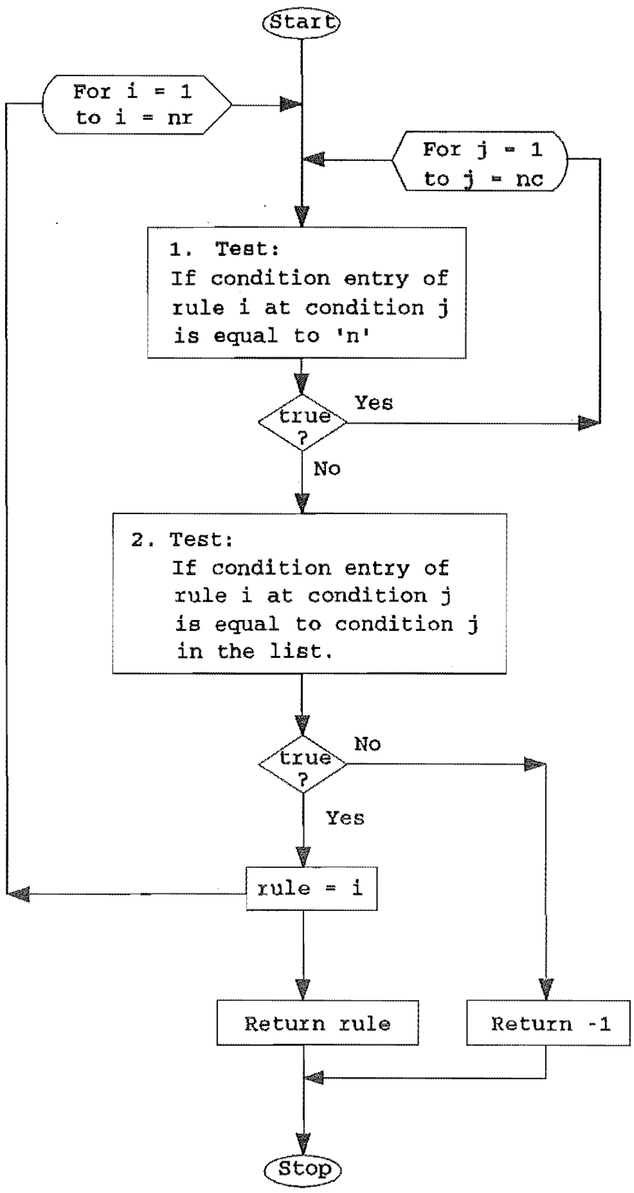
Fig.2 is called an "extended-entry" table. In this type of decision table, the elements of the condition entry and condition action have any value.

Fig.3 shows another type of decision table, called a "limited-entry" table, where the answers to the questions are of YES-NO type. Each element of the condition entry is either 'Y' for 'yes', 'N' for 'no', or '_' for 'not applicable'. These values are coded in this figure as follows: '1' for 'Y', '0' for 'N', and 'n' for '_'. AS for the action entry, it consists of 'X' to specify the action(s) in the action stub to be executed.

CAPPFD uses only limited-entry tables.

2. Processing of decision tables in CAPPFD

The CAPPFD system uses a subprogram to process the decision tables. All the condition entry matrices and the lists of conditions to be tested are passed, by address, from the calling subprograms. If the conditions in the list match with those in one of the rules, the rule number will be passed back to the calling subprogram for further action(s). However, if no rule is found, it will return -1. The flowchart for processing the decision tables is shown in Fig.4.



NOTE: nr = number of rules
nc = number of conditions

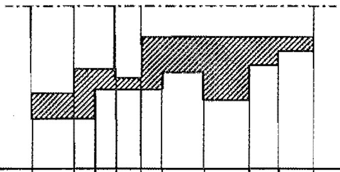
Fig.4: Flowchart for processing decision tables.

APPENDIX C

Some results from the testing of tolerance chart program

Four sets of the results are presented in this appendix. Each set consists of two figures, one showing the results from manual calculations, the other showing the results from the program. The manual calculations are taken from Ref [61, 63, 67 and 68]. Also shown in the latter are the contents of the data file for running the program.

Set 1:



CUT NO.	OP. NO.	FACE CUT	M/C	WORKING DIM. BASIC	+/-TOL.	A	B	C	D	E	F	G	H	I	J	STOCK DIM. BASIC	+/-TOL.
0																	
1				75.60	0.015											solid	
2				19.00	0.005											solid	
3				60.20	0.030											solid	
4				56.50	0.005											0.10	0.025
5				17.30	0.010											solid	
6				14.80	0.010											solid	
7				10.10	0.005											solid	
8				21.10	0.005											solid	
9				75.40	0.005											0.10	0.015
10				19.00	0.003											0.10	0.013
11				15.10	0.010											solid	
12				56.30	0.003											0.10	0.011
13				35.20	0.002											0.10	0.015
14				11.00	0.003											0.10	0.018
15				35.10	0.002											0.10	0.004
16				35.00	0.001											0.10	0.003
17				11.00	0.001											0.10	0.007
18				56.10	0.001											0.10	0.008
19				54.00	0.002											0.10	0.010
20				18.00	0.002											0.10	0.030
21				3.00	0.004											solid	
22				56.00	0.003											0.10	0.004
23				24.00	0.005											0.10	0.045
24																	
25																	
26																	
27																	
28				BLUEPRINT												RESULTANTS	
29				10.00	0.100											10.00	0.005
30				15.00	0.060											15.00	0.055
31				3.00	0.050											3.00	0.004
32				21.00	0.050											21.00	0.004
33				9.00	0.060											9.00	0.060
34				15.00	0.020											15.00	0.011
35				17.00	0.010											17.00	0.003
36				4.00	0.020											4.00	0.017
37				15.00	0.020											15.00	0.020
38																	
39																	
40																	
41																	
42																	
43																	
44																	
45																	

ALL DIMENSIONS ARE IN MILLIMETRES.

Fig.1: Manual calculations of tolerance chart [61].

```
#  0:- metal removal:  0.000 +/- 0.000
#  1:- metal removal:  0.000 +/- 0.000
#  2:- metal removal:  0.000 +/- 0.000
#  3:- metal removal:  0.000 +/- 0.000
#  4:- metal removal:  0.100 +/- 0.025
#  5:- metal removal:  0.000 +/- 0.000
#  6:- metal removal:  0.000 +/- 0.000
#  7:- metal removal:  0.000 +/- 0.000
#  8:- metal removal:  0.000 +/- 0.000
#  9:- metal removal:  0.100 +/- 0.015
# 10:- metal removal:  0.100 +/- 0.013
# 11:- metal removal:  0.000 +/- 0.000
# 12:- metal removal:  0.100 +/- 0.011
# 13:- metal removal:  0.100 +/- 0.015
# 14:- metal removal:  0.100 +/- 0.018
# 15:- metal removal:  0.100 +/- 0.004
# 16:- metal removal:  0.100 +/- 0.003
# 17:- metal removal:  0.100 +/- 0.007
# 18:- metal removal:  0.100 +/- 0.008
# 19:- metal removal:  0.100 +/- 0.010
# 20:- metal removal:  0.100 +/- 0.030
# 21:- metal removal:  0.000 +/- 0.000
# 22:- metal removal:  0.100 +/- 0.004
# 23:- metal removal:  0.100 +/- 0.045
```

```
0
9
B C E E F G H I J
A A D A C F G H I
10.0 15.0 3.0 21.0 9.0 15.0 17.0 4.0 15.0
.10 .06   .05 .05  .06 .02  .01  .02 .02
23
A J J H H G A A A J J H H E E H E H E E E H A
J H C A G F B E J H I A E B H E B A J G D A F
.015 .005 .030 .005 .010 .010 .005 .005 .005 .003 .010 .003
.002 .003 .002 .001 .001 .001 .002 .002 .004 .003 .005
0    0    0    .1   0    0    0    0    .1   .1   0    .1
.1   .1   .1   .1   .1   .1   .1   .1   0    .1   .1
0 0 0 -1 0 0 0 0 -1 1 0 -1 -1 -1 -1 -1 -1 -1 -1 1 0 -1 -1
```

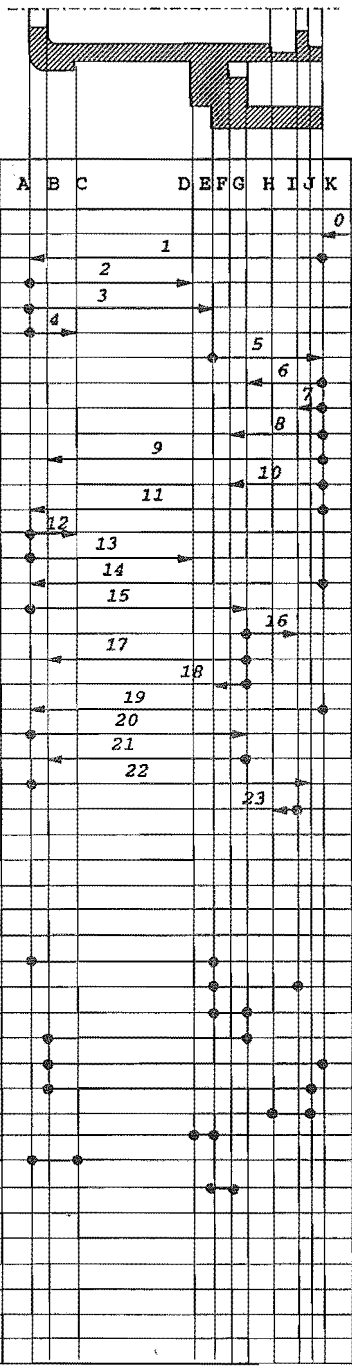
(a) Contents of data file.

```
  #  0:-
  #  1:- wrk. dim.: 75.600 +/- 0.015
  #  2:- wrk. dim.: 19.000 +/- 0.005
  #  3:- wrk. dim.: 60.200 +/- 0.030
  #  4:- wrk. dim.: 56.500 +/- 0.005
  #  5:- wrk. dim.: 17.300 +/- 0.010
  #  6:- wrk. dim.: 14.800 +/- 0.010
  #  7:- wrk. dim.: 10.100 +/- 0.005
  #  8:- wrk. dim.: 21.100 +/- 0.005
  #  9:- wrk. dim.: 75.400 +/- 0.005
  # 10:- wrk. dim.: 19.000 +/- 0.003
  # 11:- wrk. dim.: 15.100 +/- 0.010
  # 12:- wrk. dim.: 56.300 +/- 0.003
  # 13:- wrk. dim.: 35.200 +/- 0.002
  # 14:- wrk. dim.: 11.000 +/- 0.003
  # 15:- wrk. dim.: 35.100 +/- 0.002
  # 16:- wrk. dim.: 35.000 +/- 0.001
  # 17:- wrk. dim.: 11.000 +/- 0.001
  # 18:- wrk. dim.: 56.100 +/- 0.001
  # 19:- wrk. dim.: 54.000 +/- 0.002
  # 20:- wrk. dim.: 18.000 +/- 0.002
  # 21:- wrk. dim.:  3.000 +/- 0.004
  # 22:- wrk. dim.: 56.000 +/- 0.003
  # 23:- wrk. dim.: 24.000 +/- 0.005
from B to A: dwg. dim.= 10.000 +/- 0.100; resultant = 10.000 +/- 0.005
from C to A: dwg. dim.= 15.000 +/- 0.060; resultant = 15.000 +/- 0.055
from E to D: dwg. dim.=  3.000 +/- 0.050; resultant =  3.000 +/- 0.004
from E to A: dwg. dim.= 21.000 +/- 0.050; resultant = 21.000 +/- 0.004
from F to C: dwg. dim.=  9.000 +/- 0.060; resultant =  9.000 +/- 0.060
from G to F: dwg. dim.= 15.000 +/- 0.020; resultant = 15.000 +/- 0.011
from H to G: dwg. dim.= 17.000 +/- 0.010; resultant = 17.000 +/- 0.003
from I to H: dwg. dim.=  4.000 +/- 0.020; resultant =  4.000 +/- 0.017
from J to I: dwg. dim.= 15.000 +/- 0.020; resultant = 15.000 +/- 0.020
```

(b) Computer outputs.

Fig.2: Data file and computer outputs.

Set 2:



CUT NO.	OP. NO.	FACE CUT	M/C	WORKING DIM. BASIC	WORKING DIM. +/-TOL.	A B C D E F G H I J K	STOCK DIM. BASIC	STOCK DIM. +/-TOL.
0						0		
1				49.078	0.254	1	solid	
2				30.562	0.076	2	solid	
3				32.761	0.127	3	solid	
4				13.906	0.064	4	solid	
5				14.031	0.076	5	2.286	0.457
6				7.988	0.102	6	solid	
7				3.061	0.076	7	solid	
8				10.421	0.102	8	solid	
9				40.693	0.076	9	solid	
10				10.650	0,051	10	0.229	0.153
11				46.348	0.038	11	0.444	0.241
12				12.878	0.076	12	0.584	0.381
13				30.728	0.089	13	0.610	0.406
14				46.272	0.013	14	0.076	0.051
15				37.573	0.038	15	0.711	0.153
16				6.159	0.038	16	0.521	0.165
17				32.222	0.051	17	0.228	0.178
18				4.151	0.038	18	1.181	0.165
19				46.170	0.013	19	0.102	0.026
20				37.280	0.025	20	0.191	0.089
21				32.260	0.038	21	0.229	0.178
22				44.340	0.051	22	solid	
23				2.150	0.191	23	solid	
24								
25								
26								
27								
28				BLUEPRINT			RESULTANTS	
29				33.320	0.127		33.320	0.102
30				10.310	0.254		10.310	0.076
31				3.960	0.127		3.960	0.127
32				32.260	0.508		32.260	0.038
33				41.150	0.127		41.150	0.076
34				39.320	0.051		39.320	0.114
35				2.860	0.191		2.860	0.344
36				2.770	0.254		2.770	0.216
37				12.700	0.127		12.700	0.127
38				2.200	0.254		2.200	0.140
39								
40								
41								
42								
43								
44								
45								

ALL DIMENSIONS ARE IN MILLIMETRES.

Fig.3: Manual calculations of tolerance chart [63].

```
#  0:- metal removal:  0.000 +/- 0.000
#  1:- metal removal:  0.000 +/- 0.000
#  2:- metal removal:  0.000 +/- 0.000
#  3:- metal removal:  0.000 +/- 0.000
#  4:- metal removal:  2.360 +/- 0.191
#  5:- metal removal:  0.000 +/- 0.000
#  6:- metal removal:  0.000 +/- 0.000
#  7:- metal removal:  1.600 +/- 0.445
#  8:- metal removal:  1.600 +/- 0.445
#  9:- metal removal:  1.200 +/- 0.128
# 10:- metal removal:  0.000 +/- 0.000
# 11:- metal removal:  1.200 +/- 0.128
# 12:- metal removal:  1.220 +/- 0.256
# 13:- metal removal:  0.000 +/- 0.000
# 14:- metal removal:  1.220 +/- 0.256
# 15:- metal removal:  0.000 +/- 0.000
# 16:- metal removal:  0.000 +/- 0.000
# 17:- metal removal:  0.000 +/- 0.000
# 18:- metal removal:  0.380 +/- 0.089
# 19:- metal removal:  0.380 +/- 0.089
# 20:- metal removal:  0.380 +/- 0.166
# 21:- metal removal:  0.380 +/- 0.166
# 22:- metal removal:  0.000 +/- 0.000
  #  0:-
  #  1:- wrk. dim.: 46.820 +/- 0.127
  #  2:- wrk. dim.: 11.870 +/- 0.127
  #  3:- wrk. dim.: 35.700 +/- 0.127
  #  4:- wrk. dim.:  9.510 +/- 0.064
  #  5:- wrk. dim.: 26.980 +/- 0.064
  #  6:- wrk. dim.: 11.100 +/- 0.064
  #  7:- wrk. dim.: 42.860 +/- 0.127
  #  8:- wrk. dim.: 31.740 +/- 0.127
  #  9:- wrk. dim.:  8.310 +/- 0.064
  # 10:- wrk. dim.: 11.110 +/- 0.064
  # 11:- wrk. dim.:  7.110 +/- 0.064
  # 12:- wrk. dim.: 29.400 +/- 0.064
  # 13:- wrk. dim.: 26.600 +/- 0.064
  # 14:- wrk. dim.: 13.520 +/- 0.064
  # 15:- wrk. dim.:  4.070 +/- 0.064
  # 16:- wrk. dim.:  5.130 +/- 0.064
  # 17:- wrk. dim.:  4.370 +/- 0.064
  # 18:- wrk. dim.:  6.730 +/- 0.025
  # 19:- wrk. dim.:  6.350 +/- 0.064
  # 20:- wrk. dim.: 30.160 +/- 0.013
  # 21:- wrk. dim.: 14.280 +/- 0.013
  # 22:- wrk. dim.: 11.910 +/- 0.038
from A to B: dwg. dim.=  1.600 +/- 0.254; resultant =  1.600 +/- 0.217
from A to C: dwg. dim.=  2.360 +/- 0.254; resultant =  2.360 +/- 0.217
from A to D: dwg. dim.=  6.350 +/- 0.254; resultant =  6.350 +/- 0.064
from D to E: dwg. dim.=  3.180 +/- 0.254; resultant =  3.180 +/- 0.217
from A to F: dwg. dim.= 10.800 +/- 0.254; resultant = 10.800 +/- 0.217
from D to K: dwg. dim.= 30.160 +/- 0.025; resultant = 30.160 +/- 0.013
from G to H: dwg. dim.=  2.370 +/- 0.051; resultant =  2.370 +/- 0.051
from A to I: dwg. dim.= 30.160 +/- 0.254; resultant = 30.160 +/- 0.344
from H to K: dwg. dim.= 15.880 +/- 0.025; resultant = 15.880 +/- 0.026
from J to K: dwg. dim.=  3.180 +/- 0.254; resultant =  3.180 +/- 0.166
from A to L: dwg. dim.= 41.280 +/- 0.254; resultant = 41.280 +/- 0.344
```

(b) Computer outputs.

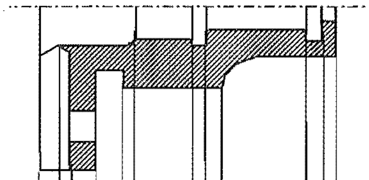
```
0
11
A A A D A D G A H J A
B C D E F K H I K K L
1.60 2.36 6.35 3.18 10.80 30.16 2.37 30.16 15.88 3.18 41.28
.254 .254 .254 .254 .254  .025  .051 .254  .025  .254 .254
22
A A A D D D A A A A D D D D D D D A D D D D
L D I A K H L I D E A K J H F B C D A K H G
.127 .127 .127 .064 .064 .064 .127 .127 .064 .064
.064 .064 .064 .064 .064 .064 .064 .025 .064 .013 .013 .038
0.0   0.0  0.0 2.36  0.0  0.0 1.60 1.60 1.20  0.0
1.20 1.22  0.0 1.22  0.0  0.0  0.0  .38  .38  .38  .38  0.0

0 0 0 -1 0 0 -1 -1 -1 0 -1 1 0 1 0 0 0 -1 -1 1 1 0
```

(a) Contents of data file.

Fig.4: Data file and computer outputs.

Set 3:



CUT NO.	OP. NO.	FACE CUT	M/C	WORKING DIM. BASIC	WORKING DIM. +/-TOL.	A B C D E F G H I J K L	STOCK DIM. BASIC	STOCK DIM. +/-TOL.
0								
1				46.82	0.127		solid	
2				11.87	0.127		solid	
3				35.70	0.127		solid	
4				9.51	0.064		2.36	0.191
5				26.98	0.064		solid	
6				11.10	0.064		solid	
7				42.86	0.127		1.60	0.445
8				31.74	0.127		1.60	0.445
9				8.31	0.064		1.20	0.128
10				11.11	0.064		solid	
11				7.11	0.064		1.20	0.128
12				29.40	0.064		1.22	0.256
13				26.60	0.064		solid	
14				13.52	0.064		1.22	0.256
15				4.07	0.064		solid	
16				5.13	0.064		solid	
17				4.37	0.064		solid	
18				6.73	0.025		0.38	0.089
19				6.35	0.064		0.38	0.089
20				30.16	0.013		0.38	0.166
21				14.28	0.013		0.38	0.166
22				11.91	0.038		solid	
23								
24								
25								
26								
27								
28				BLUEPRINT			RESULTANTS	
29				1.60	0.254		1.60	0.127
30				2.36	0.254		2.36	0.127
31				6.35	0.254		6.35	0.064
32				3.18	0.254		3.18	0.127
33				10.80	0.254		10.80	0.127
34				30.16	0.025		30.16	0.013
35				2.37	0.051		2.37	0.051
36				30.16	0.254		30.16	0.344
37				15.88	0.025		15.88	0.026
38				3.18	0.254		3.18	0.166
39				41.28	0.254		41.28	0.344
40								
41								
42								
43								
44								
45								

ALL DIMENSIONS ARE IN MILLIMETRES.

Fig.5: Manual calculations of tolerance chart [67].

```
0

10
A E E B B B H D A E
E I G G K J J E C F
33.32 10.31  3.96 32.26 41.15 39.32  2.86  2.77  12.70  2.20
.127  .254   .127 .508  .127  .051   .191  .254  .127  .254

23
K A A A E K K K K K K A A K A G G G K A G A I
A D E C K G I F B F A C D A G I B E A G B J H
.254 .076 .127 .064 .076 .102 .076 .102 .076 .051
.038 .076 .089 .013 .038 .038 .051 .038 .013 .025 .038 .051 .191
0.0    0.0    0.0    0.0    2.286 0.0   0.0    0.0    0.0    .229
.444 .584 .610 .076 .711 .521 .228 1.181 .102 .191 .229 0.0 0.0

0 0 0 0 -1 0 0 0 0 1 -1 -1 1 -1 -1 1 1 -1 -1 -1 1 0 0
```

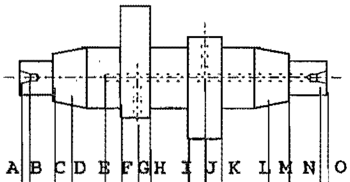
(a) Contents of data file.

```
#  0:- metal removal:  0.000 +/- 0.000
#  1:- metal removal:  0.000 +/- 0.000
#  2:- metal removal:  0.000 +/- 0.000
#  3:- metal removal:  0.000 +/- 0.000
#  4:- metal removal:  0.000 +/- 0.000
#  5:- metal removal:  2.286 +/- 0.457
#  6:- metal removal:  0.000 +/- 0.000
#  7:- metal removal:  0.000 +/- 0.000
#  8:- metal removal:  0.000 +/- 0.000
#  9:- metal removal:  0.000 +/- 0.000
# 10:- metal removal:  0.229 +/- 0.153
# 11:- metal removal:  0.444 +/- 0.241
# 12:- metal removal:  0.584 +/- 0.381
# 13:- metal removal:  0.610 +/- 0.406
# 14:- metal removal:  0.076 +/- 0.051
# 15:- metal removal:  0.711 +/- 0.153
# 16:- metal removal:  0.521 +/- 0.165
# 17:- metal removal:  0.228 +/- 0.178
# 18:- metal removal:  1.181 +/- 0.165
# 19:- metal removal:  0.102 +/- 0.026
# 20:- metal removal:  0.191 +/- 0.089
# 21:- metal removal:  0.229 +/- 0.178
# 22:- metal removal:  0.000 +/- 0.000
# 23:- metal removal:  0.000 +/- 0.000
  #  0:-
  #  1:- wrk. dim.: 49.078 +/- 0.254
  #  2:- wrk. dim.: 30.562 +/- 0.076
  #  3:- wrk. dim.: 32.761 +/- 0.127
  #  4:- wrk. dim.: 13.906 +/- 0.064
  #  5:- wrk. dim.: 14.031 +/- 0.076
  #  6:- wrk. dim.:  7.988 +/- 0.102
  #  7:- wrk. dim.:  3.061 +/- 0.076
  #  8:- wrk. dim.: 10.421 +/- 0.102
  #  9:- wrk. dim.: 40.693 +/- 0.076
  # 10:- wrk. dim.: 10.650 +/- 0.051
  # 11:- wrk. dim.: 46.348 +/- 0.038
  # 12:- wrk. dim.: 12.878 +/- 0.076
  # 13:- wrk. dim.: 30.728 +/- 0.089
  # 14:- wrk. dim.: 46.272 +/- 0.013
  # 15:- wrk. dim.: 37.573 +/- 0.038
  # 16:- wrk. dim.:  6.159 +/- 0.038
  # 17:- wrk. dim.: 32.222 +/- 0.051
  # 18:- wrk. dim.:  4.151 +/- 0.038
  # 19:- wrk. dim.: 46.170 +/- 0.013
  # 20:- wrk. dim.: 37.280 +/- 0.025
  # 21:- wrk. dim.: 32.260 +/- 0.038
  # 22:- wrk. dim.: 44.340 +/- 0.051
  # 23:- wrk. dim.:  2.150 +/- 0.191
 from A to E: dwg. dim.= 33.320 +/- 0.127; resultant = 33.320 +/- 0.102
 from E to I: dwg. dim.= 10.310 +/- 0.254; resultant = 10.310 +/- 0.076
 from E to G: dwg. dim.=  3.960 +/- 0.127; resultant =  3.960 +/- 0.127
 from B to G: dwg. dim.= 32.260 +/- 0.508; resultant = 32.260 +/- 0.038
 from B to K: dwg. dim.= 41.150 +/- 0.127; resultant = 41.150 +/- 0.076
 from B to J: dwg. dim.= 39.320 +/- 0.051; resultant = 39.320 +/- 0.114
 from H to J: dwg. dim.=  2.860 +/- 0.191; resultant =  2.860 +/- 0.344
 from D to E: dwg. dim.=  2.770 +/- 0.254; resultant =  2.770 +/- 0.216
 from A to C: dwg. dim.= 12.700 +/- 0.127; resultant = 12.700 +/- 0.127
 from E to F: dwg. dim.=  2.200 +/- 0.254; resultant =  2.200 +/- 0.140
```

(b) Computer outputs.

Fig.6: Data file and computer outputs.

Set 4:



CUT NO.	OP. NO.	FACE CUT	M/C	WORKING DIM. BASIC	WORKING DIM. +/-TOL.	STOCK DIM. BASIC	STOCK DIM. +/-TOL.
0							
1				1.594	0.031	stock	
2				0.750	0.031	stock	
3				1.750	0.031	stock	
4				0.750	0.031	stock	
5				4.094	0.062	stock	
6				2.437	0.005	0.063	0.067
7				1.594	0.005	0.063	0.072
8				3.937	0.005	0.094	0.041
9				0.625	0.015	solid	
10				0.809	0.010	solid	
11				1.588	0.003	0.088	0.013
12				2.162	0.003	0.088	0.044
13				3.338	0.003	0.088	0.044
14				5.500	0.015	0.031	0.025
15				3.912	0.003	0.025	0.008
16				4.691	0.010	solid	
17				0.625	0.015	solid	
18				3.937	0.015	solid	
19				1.875	0.015	solid	
20				3.625	0.015	solid	
21				0.125	0.010	solid	
22				5.250	0.002	solid	
23				0.732	0.010	0.048	0.030
24				3.786	0.010	0.048	0.040
25				0.750	0.005	0.018	0.015
26				3.750	0.001	0.018	0.026
27				0.719	0.002	0.006	0.020
28				2.469	0.002	0.006	0.020
29				1.281	0.002	0.006	0.020
30				3.031	0.002	0.006	0.020
31				BLUEPRINT		RESULTANTS	
32				0.125	0.015	0.125	0.010
33				0.625	0.015	0.625	0.015
34				0.875	0.015	0.875	0.015
35				0.625	0.015	0.625	0.015
36				1.875	0.015	1.875	0.015
37				3.625	0.015	3.625	0.015
38				3.937	0.015	3.937	0.015
39				0.719	0.002	0.719	0.002
40				1.281	0.002	1.281	0.002
41				2.469	0.002	2.469	0.002
42				3.031	0.002	3.031	0.002
43				3.750	0.001	3.750	0.001
44				5.250	0.002	5.250	0.002
45				5.500	0.015	5.500	0.015

ALL DIMENSIONS ARE IN INCHES.

Fig.7: Manual calculations of tolerance chart [68].

```
#  0:- metal removal:  0.000 +/- 0.000
#  1:- metal removal:  0.000 +/- 0.000
#  2:- metal removal:  0.000 +/- 0.000
#  3:- metal removal:  0.000 +/- 0.000
#  4:- metal removal:  0.000 +/- 0.000
#  5:- metal removal:  0.000 +/- 0.000
#  6:- metal removal:  0.063 +/- 0.067
#  7:- metal removal:  0.063 +/- 0.072
#  8:- metal removal:  0.094 +/- 0.041
#  9:- metal removal:  0.000 +/- 0.000
# 10:- metal removal:  0.000 +/- 0.000
# 11:- metal removal:  0.088 +/- 0.013
# 12:- metal removal:  0.088 +/- 0.044
# 13:- metal removal:  0.088 +/- 0.044
# 14:- metal removal:  0.031 +/- 0.025
# 15:- metal removal:  0.025 +/- 0.008
# 16:- metal removal:  0.000 +/- 0.000
# 17:- metal removal:  0.000 +/- 0.000
# 18:- metal removal:  0.000 +/- 0.000
# 19:- metal removal:  0.000 +/- 0.000
# 20:- metal removal:  0.000 +/- 0.000
# 21:- metal removal:  0.000 +/- 0.000
# 22:- metal removal:  0.000 +/- 0.000
# 23:- metal removal:  0.048 +/- 0.030
# 24:- metal removal:  0.048 +/- 0.040
# 25:- metal removal:  0.018 +/- 0.015
# 26:- metal removal:  0.018 +/- 0.026
# 27:- metal removal:  0.006 +/- 0.020
# 28:- metal removal:  0.006 +/- 0.020
# 29:- metal removal:  0.006 +/- 0.020
# 30:- metal removal:  0.006 +/- 0.020
  #  0:-
  #  1:- stc. dim.:  1.594 +/- 0.031 (A-F)
  #  2:- stc. dim.:  0.750 +/- 0.031 (F-H)
  #  3:- stc. dim.:  1.750 +/- 0.031 (F-I)
  #  4:- stc. dim.:  0.750 +/- 0.031 (I-K)
  #  5:- stc. dim.:  4.094 +/- 0.062 (F-O)
  #  6:- wrk. dim.:  2.437 +/- 0.005
  #  7:- wrk. dim.:  1.594 +/- 0.005
  #  8:- wrk. dim.:  3.937 +/- 0.005
  #  9:- wrk. dim.:  0.625 +/- 0.015
  # 10:- wrk. dim.:  0.809 +/- 0.010
  # 11:- wrk. dim.:  1.588 +/- 0.003
  # 12:- wrk. dim.:  2.162 +/- 0.003
  # 13:- wrk. dim.:  3.338 +/- 0.003
  # 14:- wrk. dim.:  5.500 +/- 0.015
  # 15:- wrk. dim.:  3.912 +/- 0.003
  # 16:- wrk. dim.:  4.691 +/- 0.010
  # 17:- wrk. dim.:  0.625 +/- 0.015
  # 18:- wrk. dim.:  3.937 +/- 0.015
  # 19:- wrk. dim.:  1.875 +/- 0.015
  # 20:- wrk. dim.:  3.625 +/- 0.015
  # 21:- wrk. dim.:  0.125 +/- 0.010
  # 22:- wrk. dim.:  5.250 +/- 0.002
  # 23:- wrk. dim.:  0.732 +/- 0.010
  # 24:- wrk. dim.:  3.786 +/- 0.010
  # 25:- wrk. dim.:  0.750 +/- 0.005
  # 26:- wrk. dim.:  3.750 +/- 0.001
  # 27:- wrk. dim.:  0.719 +/- 0.002
  # 28:- wrk. dim.:  2.469 +/- 0.002
  # 29:- wrk. dim.:  1.281 +/- 0.002
  # 30:- wrk. dim.:  3.031 +/- 0.002
```

```
5
A F F I F
F H I K O
0.031 0.031 0.031 0.031 0.062
14
A A A N A A E D D D D D B A
B C D O G J O F H I K L N O
.125 .625 .875 .625 1.875 3.625 3.937 .719 1.281 2.469
3.031 3.750 5.250 5.500
.015 .015 .015 .015  .015  .015  .015 .002  .002  .002
.002   .001  .002  .015
25
F K K A A A A A A A A O O A A A B B D B D D D D D
K O A C D F H I O K L M E G J B N D L D L F I H K
.005 .005 .005 .015 .010 .003 .003 .003 .015 .003
.010 .015 .015 .015 .015 .010 .002 .010 .010 .005
.001 .002 .002 .002 .002
.063 .063 .094 .0   .0   .088 .088 .089 .031 .025
.0   .0   .0   .0   .0   .0   .0   .048 .048 .018
.018 .006 .006 .006 .006
-1 -1 -1 0 0 1 -1 1 -1 -1 0 0 0 0 0 0 0 1 -1 1 -1 1 1 -1 -1
```

(a) Contents of data file.

```
from A to B: dwg. dim.=  0.125 +/- 0.015; resultant =  0.125 +/- 0.010
from A to C: dwg. dim.=  0.625 +/- 0.015; resultant =  0.625 +/- 0.015
from A to D: dwg. dim.=  0.875 +/- 0.015; resultant =  0.875 +/- 0.015
from M to O: dwg. dim.=  0.625 +/- 0.015; resultant =  0.625 +/- 0.015
from A to G: dwg. dim.=  1.875 +/- 0.015; resultant =  1.875 +/- 0.015
from A to J: dwg. dim.=  3.625 +/- 0.015; resultant =  3.625 +/- 0.015
from E to O: dwg. dim.=  3.937 +/- 0.015; resultant =  3.937 +/- 0.015
from D to F: dwg. dim.=  0.719 +/- 0.002; resultant =  0.719 +/- 0.002
from D to H: dwg. dim.=  1.281 +/- 0.002; resultant =  1.281 +/- 0.002
from D to I: dwg. dim.=  2.469 +/- 0.002; resultant =  2.469 +/- 0.002
from D to K: dwg. dim.=  3.031 +/- 0.002; resultant =  3.031 +/- 0.002
from D to L: dwg. dim.=  3.750 +/- 0.001; resultant =  3.750 +/- 0.001
from B to N: dwg. dim.=  5.250 +/- 0.002; resultant =  5.250 +/- 0.002
from A to O: dwg. dim.=  5.500 +/- 0.015; resultant =  5.500 +/- 0.015
```

(b) Computer outputs.

Fig.8: Data file and computer outputs.

APPENDIX D

The method of traces for checking accumulated tolerance

The following is the excerpt on the method of traces taken from Ref [61]. Prior to the rooted-tree method, it was commonly used in manual tolerance charting. The method is presented here for a comparison with the method developed in this project.

To Check the Accumulation of the Balance-dimension Tolerances and the Resultant-dimension Tolerances:

1. Trace upward simultaneously from the left and the right extremity of the dimension in question.
2. Make a horizontal turn with the trace which first encounters an arrowhead of a working dimension.
3. With that trace move horizontally to the end of that working dimension, and then turn vertically upward.
4. With the other trace move in a similar fashion along its path.
5. As necessary for convergence (see step 6) continue with both traces to the next arrowheads and repeat step 3 for each.
6. At the point where both traces converge, the process stops. (Convergence of traces is defined as the first point at which both traces would be going upward along the same vertical line. Remember that the crossing of traces is not convergence!)
7. Add all the tolerances of the working dimensions where

horizontal turns were made. This total is the tolerance for the balance or the resultant dimension in question.

NOTE: Stock-dimension tolerances are not and must not be used at any time in the foregoing steps.

To Check the Accumulation of Stock-removal Tolerances for Each Working Dimension:

The same procedure is followed as for the balance and resultant dimensions (shown above), except that the tolerance of the working dimension for which the stock-removal tolerance is required must also be added to the total. Those will result in the stock-removal tolerance at this working dimension.

Examples

Let us examine several representative examples which show how this method works.

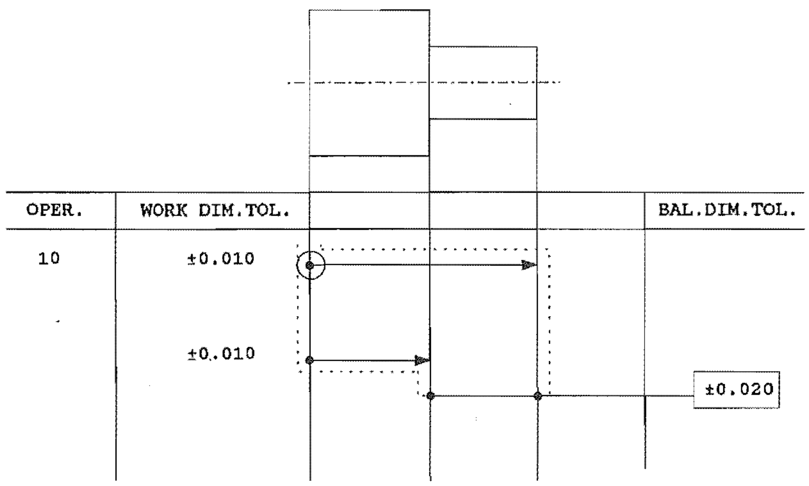


Fig.1: Calculation of balance-dimension tolerance.

Example 1 (Fig.1)

The traces (broken lines) are shown beginning at the left and the right extremities of the balance dimension in question. The point of convergence is circled. Two horizontal turns are made. These are valued at +0.010 each, or a total of +0.020, which is the tolerance for the balance dimension. Note that the mean dimensions are not necessary for this check. Also in the actual practice the paths of the traces are not shown on the tolerance chart. They are used here to illustrate the method.

Example 2 (Fig.2)

In this example a resultant dimension is computed in a manner similar to Example 1 for a balance-dimension tolerance. Notice how the traces cross each other and where convergence takes place.

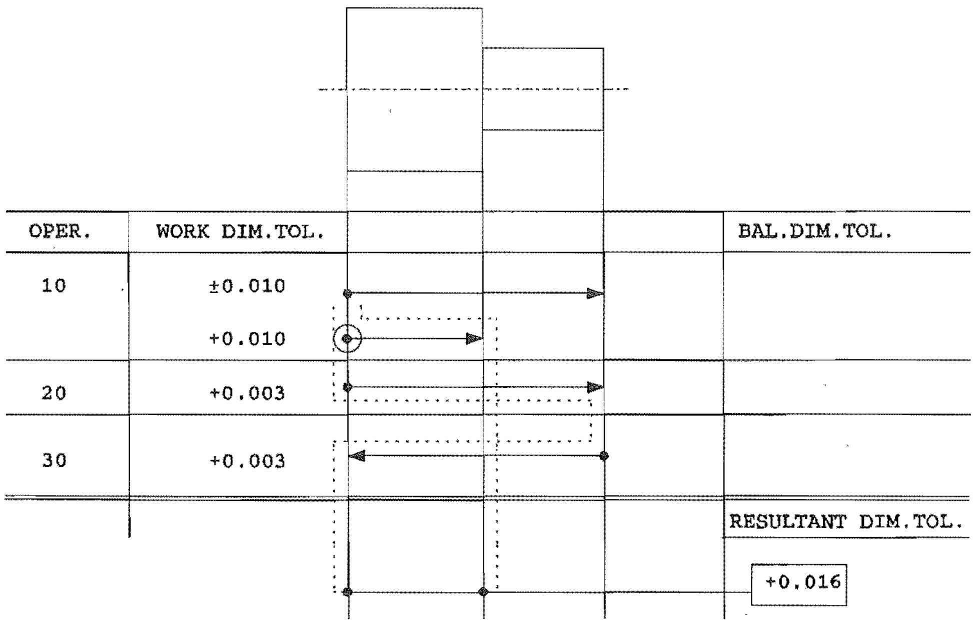


Fig.2: Calculation of resultant-dimension tolerance.

Example 3 (Fig.3)

In this example the method of traces is used to check a stock-removal tolerance. The method is the same as for balance- and resultant-dimension tolerances except that the tolerance of the working dimension for which the stock-removal tolerance is computed is also added to the total.

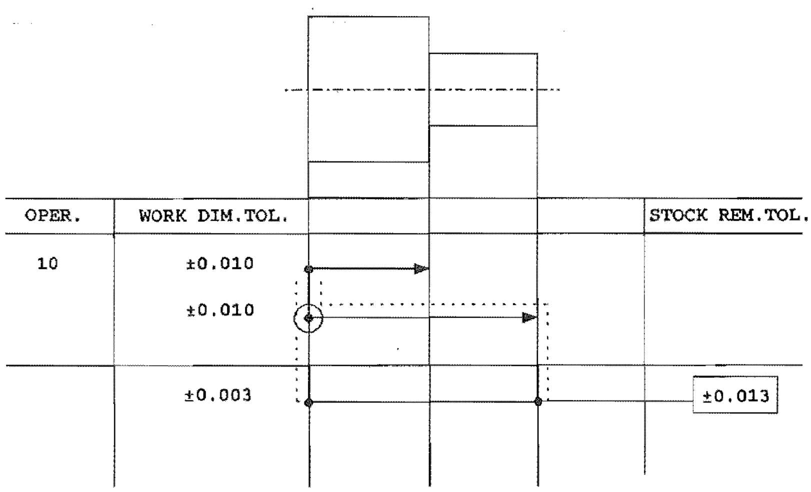


Fig.3: Calculation of stock-removal tolerance.